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CONCEPTS FOR 18/30 GHz SATELLITE COMMUNICATION SYSTEM STUDY

VOLUME I - FINAL REPORT

Contract NAS3-21362

Prepared for:
NASA LEWIS RESEARCH CENTER
Cleveland, Ohio

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3939 Fabian Way
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ABBREVIATIONS

AACS	attitude and antenna control subsystem
AGC	automatic gain control
BER	bit error rate
BOL	beginning of life
BPSK	binary phase shift keying
CCIR	International Radio Consultative Committee
CER	cost estimating relationship
CONUS	Continental United States
DCC	Digital Communications Corporation
DTU	direct-to-user
EIRP	effective isotropic radiated power
EOL	end of life
FACC	Ford Aerospace & Communications Corporation
FDM	frequency division multiplex
FDMA	frequency division multiple access
FET	field effect transistor
FSI	Future Systems Incorporated
GFRP	glass fiber reinforced plastic
G/T	gain-to-noise-temperature ratio
HPA	high power amplifier
IF	intermediate frequency
IM	intermodulation
LNA	low noise amplifier
LSI	large scale integration
IUS	interim upper stage
MBA	multiple beam antenna
MOSFET	metal oxide semiconductor field effect transistor
MTBF	mean time between failures
MTTR	mean time to repair
NEC	Nippon Electric Corporation
NF	noise figure
NR	nonrecurring
NWS	National Weather Service
O&M	operation and maintenance
PCM	pulse code modulation
PSK	phase shift keying
QPSK	quadriphase shift keying
R	recurring
rf	radio frequency
SAMSO	Space and Missile Systems Organization (USAF)
satcom	satellite communications
S/C	spacecraft
SMSA	standard metropolitan statistical areas
SOS	silicon on sapphire

SPM	satellite propulsion module
SSB	single sideband
SSUS	spin-stabilized upper stage
STS	Space Transportation System
TDA	tunnel diode amplifier
TDM	time division multiplex
TDMA	time division multiple access
TT&C	telemetry, tracking, and command
TWT	traveling wave tube
TWTA	traveling wave tube amplifier

SECTION 1

INTRODUCTION

This study report on concepts for 18/30 GHz satellite communications systems was prepared by the Western Development Laboratories (WDL) Division of Ford Aerospace & Communications Corporation (FACC) in Palo Alto, California under contract NAS3-21362 from NASA/Lewis Research Center. The effort was initiated in May 1978. The principal contributors of FACC are R. Jorasch, M. Baker, R. Davies, L. Cuccia, and Dr. C. Mitchell. The analysis of rain attenuation effects was prepared under subcontract by Future Systems, Inc., R. Stamminger and J. Stein.

Subsection 1.1

Objectives

This report defines and evaluates concepts for using K_A-band (18/30/GHz) in lieu of or in conjunction with C-band (4/6 GHz) and K_U-band (11/14 GHz). Since it is anticipated that within 10 to 15 years these bands will be fully utilized, the potential use of higher frequency bands not currently used must be examined. This report addresses the feasibility of using K_A-band for fixed service communications via satellite in the United States.

The objective of this study is to provide information that will help answer the following questions:

- Will 18/30 GHz satellite trunking into major terminals be competitive with present and future communication alternatives (such as buried waveguide, optical fiber, and satellites)? What are the probable methods of implementing this service?
- Could 18/30 GHz satellite systems provide economical services directly to the users, that is, via small inexpensive earth terminals? What are the probable methods of implementing such a service?
- What are the advanced technology efforts that need to be carried out to reduce the commercial risk of introducing such a communication system?
- What is the impact of rain attenuation on the technical and economic viability of 18/30 GHz systems, and what are the likely methods of minimizing this problem?
- What are the ultimate cost effective capacities of the 18/30 GHz bands for domestic fixed service, given current and planned technology?

A summary of the key study tasks is shown in Table 1.1-1.

Table 1.1-1. 18/30 GHz Satcom Configuration Study

• Evaluate major terminal trunking configurations • 99.9% communications availability • 200 MHz interconnect of 10 to 40 trunking sites • Multiple spot beam antenna
• Evaluate direct-to-user configuration • 99.5% communications availability • 25-40 antenna beams forming full CONUS coverage
• Determine critical technologies to support millimeter wave satellite communications in period of 1985-2000

The major terminal trunking configurations are discussed in Section 3. General requirements for this approach include communications availability of at least 99.9%, use of multiple spot beam antennas from the spacecraft, and accommodation of a network of 10 to 40 sites with 200 MHz of interconnect capacity.

The direct-to-user (DTU) configurations are presented in Section 4. General requirements include 99.5% communications availability and full CONUS coverage (48 states) with up to 40 spacecraft beams.

The critical technology to support millimeter wave communications in the period 1985-2000 is presented in Sections 2 and 5.

The matrix of candidate system configurations (Figure 1.1-1) becomes very large if each of the parameters is variable. Key decisions include number of spacecraft antenna beams, communications modulation technique, use of switching and/or processing in the spacecraft, propagation availability level, data quality, flexibility for future expansion, use of space diversity earth terminals, etc. The approach used by FACC in this study was to define a baseline approach for both trunking and DTU systems. Detailed analysis is provided on the baseline in order to provide a comprehensive framework for consideration of all variables. Alternatives to the baseline are then presented to permit tradeoff comparisons.

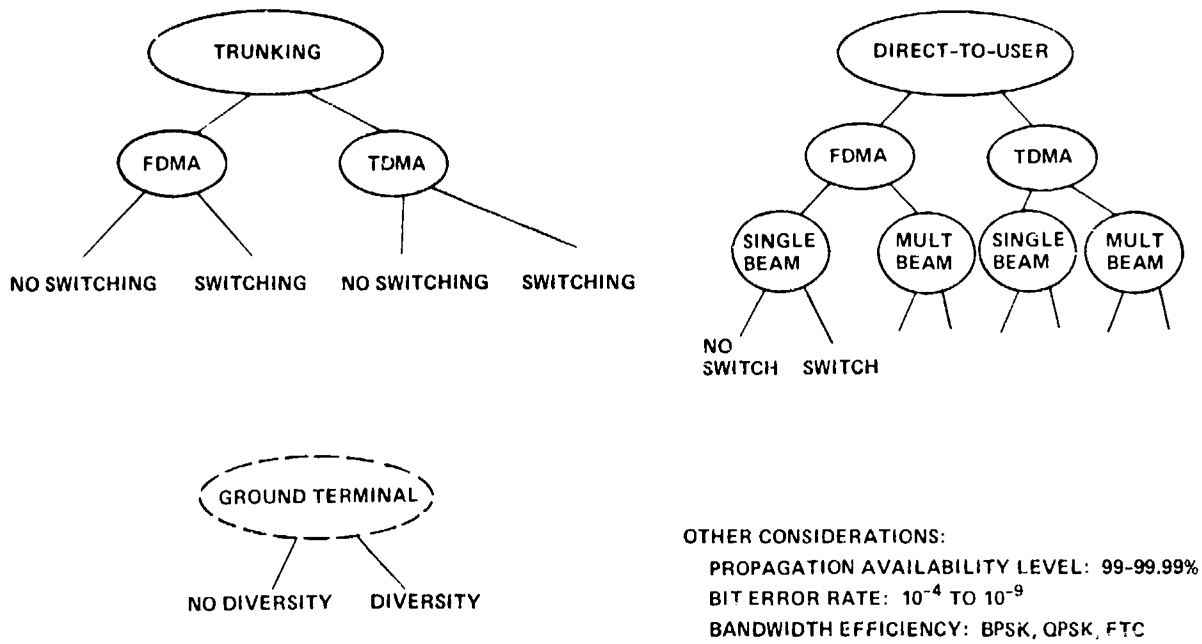


Figure 1.1-1. Matrix of Candidate System Configurations

This report presents concepts rather than an optimized design. It is expected that an optimized configuration would be determined at a later date after communications requirements are fixed and after technology developments and test are completed.

Subsection 1.2

Study Overview

The general approach used by FACC in determining baseline system concepts and viable alternative concepts is outlined in Figure 1.2-1.

It consists of the following four phases:

- System concept development
- Concept general optimization
- Sensitivity analysis
- Concept selection

Concept development begins with configuring the various systems by preparing block diagrams and selecting performance parameters. These baselines serve as a reference to which further design iterations can be compared. In the process of developing concepts, existing knowledge of technology and cost limitations are applied.

To aid in the conceptualization, a link calculation computer program was used. The program features user-interactive data options and printout format selection to meet a variety of conditions. A key input to the concept design is the rain propagation model.

Certain subsystems are optimized separately to determine the performance parameters used for system optimization. For example, the ground terminal diameter is chosen to minimize cost for a specified G/T and EIRP.

The basic cost data was generated for space and ground segments. These costs define the initial unit cost of the satellite and each ground terminal type. The space segment cost includes the launch cost (Shuttle). The space segment contains two on-orbit satellites — one operating and one spare — plus two ground spares. The annual operation and maintenance cost of the ground terminal is estimated.

As a summary overview, the general configuration of the baseline trunking system is shown in Figure 1.2-2. Ten spot beams from a geosynchronous orbit satellite illuminate the network of 10 selected trunking site locations. The earth terminals are 12 meters in diameter, and a second diversity terminal is located at each site (with separation of 8 km or more from the main terminal) to minimize the effect of rain attenuation. The spacecraft is three-axis stabilized and uses a dual reflector antenna to achieve the spot beam coverage. A full interconnect of 274 Mb/s is provided between all trunking terminals, which leads to a maximum data throughput capacity of 25 Gb/s. The baseline approach uses frequency division multiple access (FDMA) communications, and quadriphase modulation (QPSK) is used for spectrum efficiency.

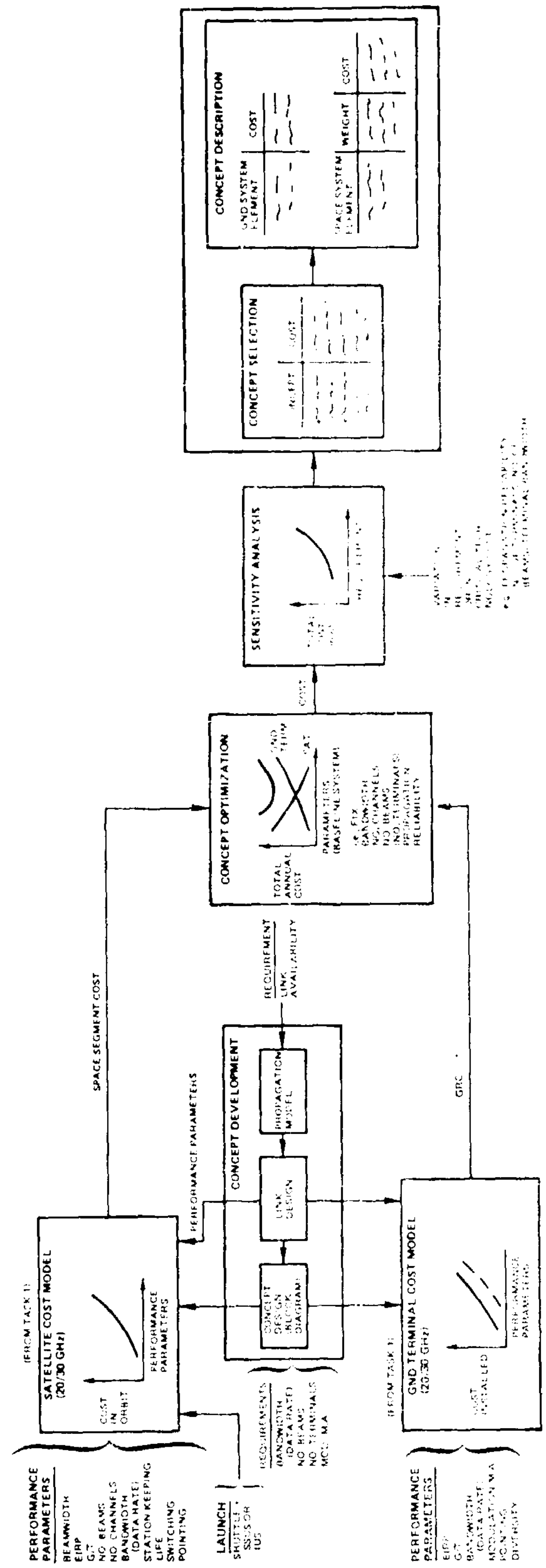


Figure 1.2-1. Approach to System Concept Definition

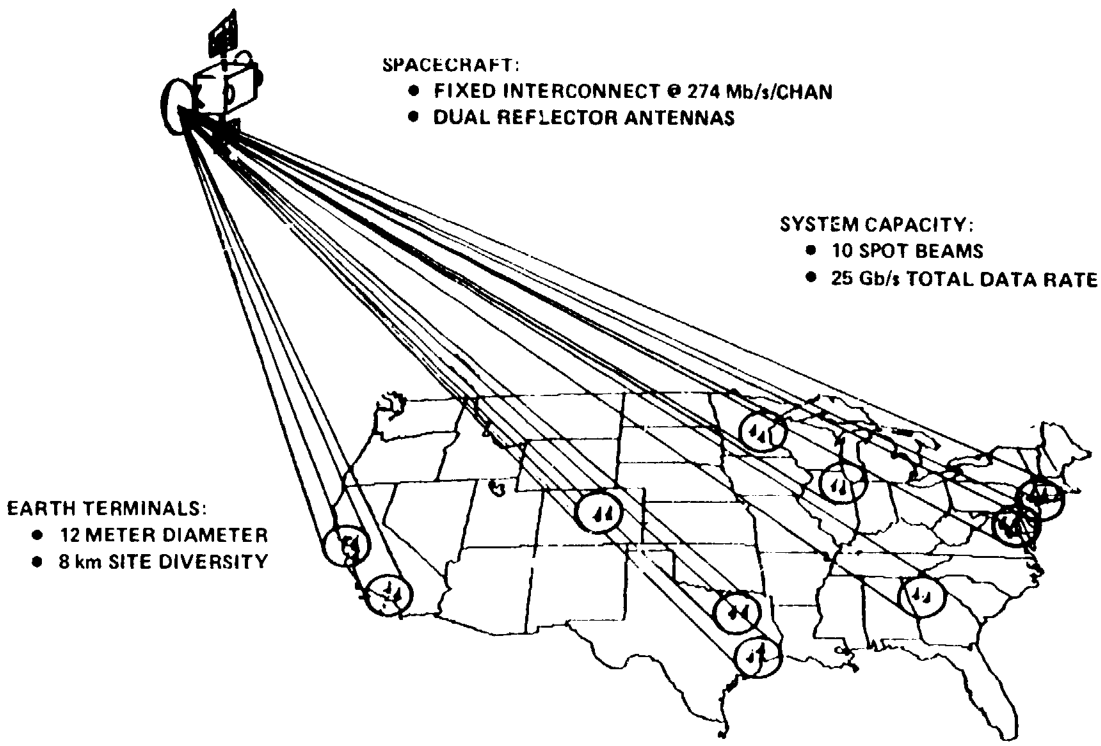


Figure 1.2-2. Trunking Network Configuration

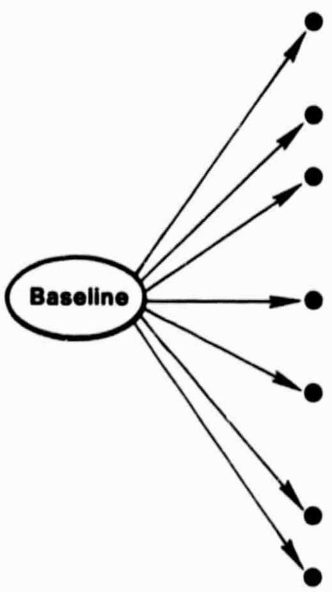
The costs generated during the study are based on a parametric model developed by FACC, which incorporates several parametric algorithms empiricaly derived by FACC and a modified version of the USAF Space and Missile Systems Organization (SAMSO) spacecraft cost model. The baseline trunking system costs are shown in Table 1.2-1. The total 10-year costs for fixed investment and operations of terminals and TT&C is expected to be $425 million. The spacecraft and launch segment make up 68% of the program costs and earth terminal fixed and operating costs make up the balance of 32% for the condition of a 10-site network.

The large fixed costs of the satellite communication (satcom) system are incurred early in the program, whereas revenue would be spread over the full operating period. After adding a cost of money it is expected that a duplex 64 kb/s channel would require $300 per year in revenue to offset the satcom costs only. A simplex 1.5 Mb/s channel would require $3600 per year. These are costs allocated per occupied bandwidth. These costs are not expected tariffs.

Figure 1.2-3 shows some of the key alternative concepts to the baseline trunking system. These alternatives include changes to the number of terminal sites, the system capacity, nonuniform channel bandwidth allocation, time division multiple access (TDMA) modulation, elimination of the diversity terminal, and increase of spacecraft power. Some of the alternatives may include combinations of parameter changes. A full discussion of trunking concepts is presented in Section 3.

Table 1.2-1. Trunking System Baseline Configuration

Baseline Design:	25 Gb/s system capacity		
	10-site coverage with 0.3° antenna beams		
	FDM with 274 Mb/s per carrier		
	Solid-state amplifiers in spacecraft		
	Diversity earth terminals of 12 m diameter		
	No onboard switching or processing		
System Costs:	Spacecraft	\$195 M	68%
(10 yr)	Launch and TT&C	\$ 95 M	
	Earth terminals fixed	\$ 78 M	32%
	Operations costs	\$ 57 M	
Allocated Circuit Costs:	Duplex 64 kb/s channel	\$ 300/yr	
(Satcom segment only)	Simplex 1.5 Mb/s channel	\$3,600/yr	



Alternative		Assessment
Increase number of sites	-	Increased complexity of S/C multiplexing but tails circuit costs reduced
Increase system capacity	-	User demand may not exceed 25 Gb/s for 1st generation
Nonuniform channel capacity	-	Recommended for more efficient match to user needs
	-	New York beam traffic limits system
TDM modulation	-	High-capacity system requires 2.5 Gb/s modulators and high-peak power transmitters
Eliminate diversity terminal	-	Saves \$3.2 M per site but communications availability decreased or space segment costs increased significantly
Increase S/C power	-	Becomes cost effective for large number of earth terminals
Collector SATCOM links within beam	-	May be included to reduce tails circuit costs

Figure 1.2-3. Trunking System Alternatives

The general configuration of the baseline DTU system is shown in Figure 1.2-4. A TDMA method of communications is used. Twenty-five coverage beams from a geosynchronous orbit satellite provide full coverage of CONUS (48 states) with half-power beamwidths of about 1°. The earth terminals are 4.5 m in diameter, and a quantity of 1000 is expected for a full network. To minimize cost, a diversity terminal at each site is not provided. The rain attenuation at 18/30 GHz reduces the communications availability to 99.5%, which corresponds to an outage of about 44 hours per year.

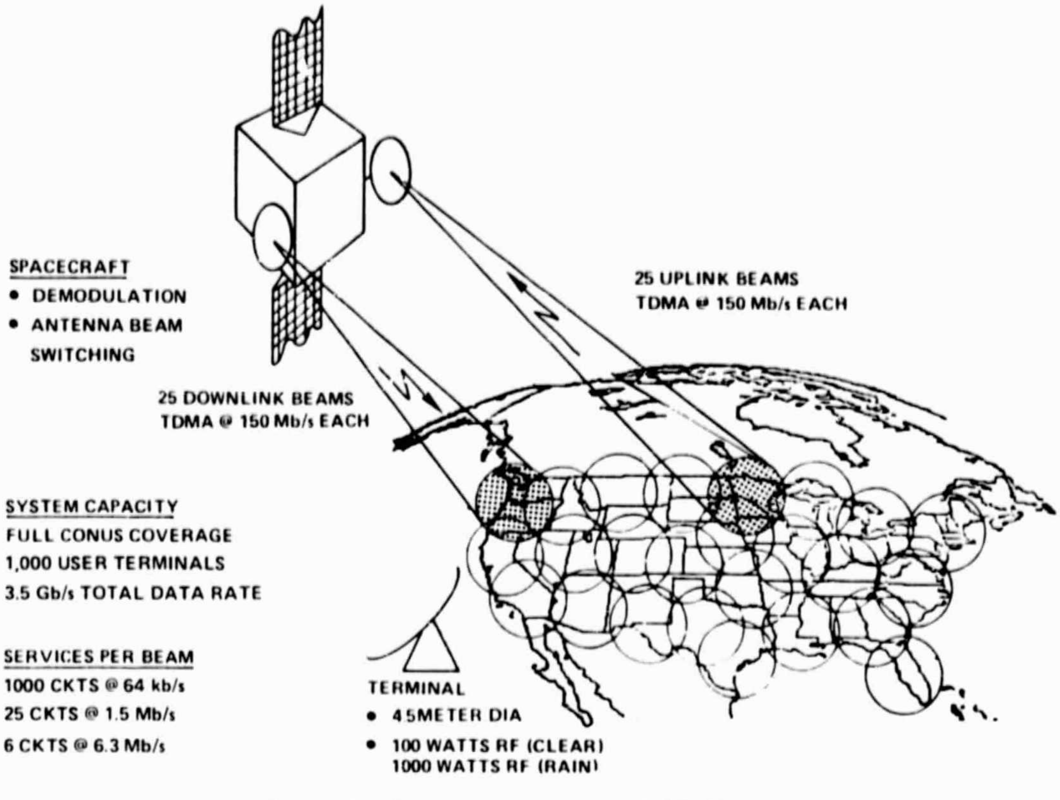


Figure 1.2-4. Direct-to-User at 18/30 GHz

Each coverage beam has a data capacity of 140 Mb/s (and burst rate of 150 Mb/s with guard time) and the services per beam would provide 1000 channels at 64 kb/s, 25 channels at 1.5 Mb/s, and 6 channels at 6.3 Mb/s. The maximum system data throughput capacity is 3.5 Gb/s.

The spacecraft is three-axis stabilized and uses four small reflector antennas to provide uplink and downlink coverage. Demodulation of each uplink signal is achieved, and a baseband switch operating at 750 reconfigurations per second is used to interconnect up and down antenna beams.

The baseline DTU system costs are shown in Table 1.2-2. The total 10-year costs for fixed investment and operations of terminals and TT&C is expected to be $1.232 billion. The spacecraft and launch segment comprises 27% of the program costs with earth terminal fixed and operating costs comprising the balance of 73% for the condition of a 1000-terminal network.

The large fixed costs of the satcom system are incurred early in the program, whereas revenue would be spread over the full operating period. After adding a cost of money it is expected that a duplex 64 kb/s channel would require $7500 per year in revenue to offset the satcom cost. A simplex 1.5 Mb/s channel would require $87,000 per year. These costs are allocated per occupied bandwidth. Again, these costs are not expected tariffs.

Table 1.2-2. Direct-to-User Baseline Configuration

Configuration:	3.5 Gb/s maximum capacity 25 beam full CONUS coverage TDM @ 150 Mb/s per beam Remodulation & antenna switching in spacecraft 1000 earth terminals of 4.5 m diameter		
System Costs:	Spacecraft	$248 M	27%
	Launch and TT&C	$ 85 M	
	Earth terminals fixed	$522 M	73%
	Earth terminals operations	$376 M	
Allocated Circuit Costs:	Duplex 64 kb/s channel	$ 7,500/yr	
	Simplex 1.5 Mb/s channel	$ 87,000/yr	
	Simplex 6.3 Mb/s channel	$365,000/yr	

Figure 1.2-5 shows some of the key alternative concepts to the baseline DTU system. These alternatives include change to the number to terminals, the system capacity, nonuniform bandwidth allocation per beam, FDMA modulation, use of onboard processing, and increased spacecraft power. Some of the alternatives may include combinations of parameter changes.

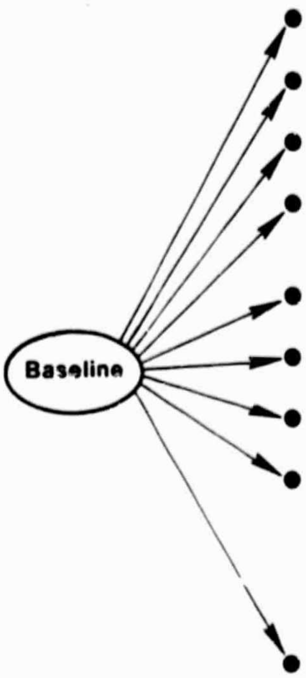
Direct-to-user concepts are discussed fully in Section 4.

The key technology developments identified for 18/30 GHz systems are summarized in Table 1.2-3.

The key developments identified for support of the baseline trunking system application are: (1) multiple spot beam spacecraft antennas with half-power beamwidth of 0.3° or less, (2) solid-state spacecraft amplifiers with rf output power of 1 W or more, (3) multichannel spacecraft filtering with low weight techniques, (4) power control for diversity earth terminal network. It also is important to promote development that assures long term (10 year) spacecraft reliability on-orbit.

The key developments identified for support of the baseline DTU system are: (1) multiple narrow beam spacecraft antenna providing full CONUS coverage, (2) spacecraft traveling wave tube (TWT) amplifiers providing 25 to 100 W rf power output at 18 GHz, (3) spacecraft demodulatyion/remodulation and baseband switching at rates of about 750 interconnect reconfigurations per second, and (4) low cost earth terminal manufacturing techniques.

Technology items are fully discussed in Sections 2 and 5.



Increase number of terminals	- Service availability decreases
Increase spacecraft power	- Small impact because of uplink limitations
Increase system capacity	- Earth terminal diameter exceeds 5 meters - too large
Allocate extra channels to high-traffic beams	- Should be incorporated for balanced system, increases switching matrix complexity
Skewed data capacity among beams	- Feasible with variable switching dwell period
Increase number of beams	- Switching matrix becomes excessive
Include onboard processing	- Efficient - however, reliability compromised, 2nd generation
FDM modulation	- Eliminates spacecraft switching – however, filters become excessive for large numbers of links - Earth terminal transmitter power reduced, but frequency synthesizer added
Decrease communications link availability	- Eliminate 5 dB down/15 dB up rain margin - reduces system cost

Figure 1.2-5. DTU Alternatives

Table 1.2-3. Key Technology at 18/30 GHz

- Spacecraft antenna
  - Multiple spot beams of 0.3° beamwidth with low sidelobe
  - Full coverage of CONUS with multibeams
- Spacecraft amplifiers
  - 1 to 5 watt solid-state amplifiers
  - 25 to 100 watt TWT for multichannel application
- Spacecraft data handling
  - Antenna switching at 750 reconfigurations per second
  - Demodulation/remodulation
- Earth terminals
  - Diversity operations with power control
  - Low-cost manufacturing techniques

Subsection 1.3

Conclusions and Recommendations

This report evaluates and defines concepts for satellite communications systems at the 18/30 GHz band. The broad scope of the study has required examination of a multiplicity of interconnected parameters ranging from specific technology details to total system economic costs.

It is determined that K_A band systems will incur a small outage during very heavy rainfall periods and that reducing the outage to zero would lead to prohibitive system costs. On the other hand, the economics of scale, ie, one spacecraft accommodating 2.5 GHz of bandwidth coupled with multiple beam frequency reuse, lead to very low costs for those users who can tolerate the 5 to 50 hours per year of downtime. It is believed that an overall multiple frequency band (C-band, K_U-band, K_A-band) satellite network will provide the ultimate optimized match to the consumer performance/economics demands.

Other general recommendations and conclusions reached by the Ford Aerospace & Communications Corporation study team are summarized in the categories of (1) technology, (2) trunking systems, (3) direct-to-user systems, and (4) future effort.

1.3.1 Technology

An assessment of the 18/30 GHz technology leads to the following recommendations and conclusions:

a. It is not expected that the technology development will present a major hurdle to a successful first generation satellite communication system. No major inventions need be scheduled.

b. A more sophisticated technology than that presented in the baseline trunking and direct-to-user system design is available (or could be developed); however, it is not required for the first generation system. The emphasis in technology should focus on 10-year on-orbit reliability to meet practical user data requirements.

c. Other countries have already been developing 18/30 GHz equipment, and the United States may lose the technology lead in this frequency band. The Japanese CS satellite, with capacity of 600 Mb/s at 18/30 GHz, was launched in December 1977 and experimental tests have continued to date.

d. Spectrum conservation will become even more important in future systems, hence spectrum-efficient QPSK modulation should be used. Also the use of narrow beam antennas will permit frequency reuse several times over for CONUS coverage.

e. There is need for a current development test program to assure long term reliability at high performance and to reduce the risk associated with fixed price bidding of the spacecraft segment. Key development items should include the following:

1. Spot beam spacecraft antennas
2. CONUS coverage spacecraft antennas with multiple beams
3. High power spacecraft TWT amplifiers up to 100 W rf output

4. Solid-state spacecraft amplifiers up to 5 W rf output
5. Lightweight, broadband, multichannel filters
6. Baseband and IF switching for spacecraft
7. Diversity earth terminal implementation techniques
8. Low cost techniques for production of direct-to-user earth terminals

1.3.2 Trunking Systems

A review of trunking systems, which are designed to accommodate large amounts of data from a relatively small number of terminals, leads to the following:

a. The total 10-year costs of developing, manufacturing, and operating a satellite trunking system of 25 Gb/s capacity among 10 earth terminal sites within CONUS is expected to range from $365 million for a TDMA configuration to $424 million for an FDMA configuration.

b. About two-thirds of the system cost is required by the satellite segment and one-third for the terminal segment (for a 10-site network); hence performance/cost optimization of the satellite segment is of key importance.

c. It is impossible to determine an optimum trunking configuration until decisions are reached on a large number of technical, economic, political, and user demand factors. Included are communications demand growth as a function of quality and circuit availability, scenarios for determining which companies will be permitted to operate and how to share the satellite network, and desirability of large multifrequency-band satellites versus smaller satellites operating at a single frequency band.

d. An initial system configuration which is to accommodate about 16 or fewer trunking sites is better served by using an FDMA modulation technique. Elimination of the need for onboard switching is expected to enhance long term reliability.

e. If the number of trunking sites is greater than about 16, then the TDMA modulation technique becomes more attractive because of the larger filter network associated with FDMA operation. The filter network for FDMA increases as the square of the number of sites.

f. The earth terminal antennas should be limited to about 12 m in diameter. A diversity terminal, separated by 8 km or more from a main terminal, should be incorporated at each site to minimize the impact of rain outage.

g. A spot beam spacecraft antenna of 0.3° half-power beamwidth appears feasible for coverage over the extremity of CONUS. A three-axis spacecraft design is recommended in order to minimize antenna pointing errors.

h. It is technically possible to accommodate 30 to 50 spot beams from the spacecraft provided that they are spaced no closer than about 0.3° with respect to the spacecraft view angle. A resolution of New York City and Washington, D.C. on separate beams represents the limit of a 14 ft diameter spacecraft antenna.

i. The spacecraft antenna should be a dual reflector type and fit within the payload bay of the Space Shuttle Orbiter such that on-orbit unfurling is not required.

j. The spacecraft transponder channel bandwidths of the baseline design should be modified to match the skewed traffic demand model in order to maximize communications efficiency.

k. An increase in the baseline spacecraft power amplifier output to a range of 2 to 4 W rf per channel is cost effective provided that solid-state amplifier technology is available at the higher power level.

l. The costs of the satcom trunking system of this report do not include the "tail circuit" costs of getting from the terminal to the ultimate user. A greater analysis of the distribution costs is required before total circuit costs can be established.

m. It is expected that maximum capacity use would result in a satellite and terminal allocated circuit cost of $3600 per year for a 1.5 Mb/s simplex channel.

1.3.3 Direct-to-User Systems

A review of direct-to-user (DTU) systems, which are designed to accommodate up to several megabits of data per second from a very large number of small user terminals (1000 to 10,000), leads to the following recommendations and conclusions:

a. The total 10-year cost of developing, manufacturing, and operating a satellite DTU system of 3.5 Gb/s capacity among 1000 user terminals located within CONUS is expected to range from $1.230 billion for a TDMA configuration to $1.555 billion for an FDMA configuration.

b. The TDMA systems are more attractive for a large number of users (ie, more than 500) whereas the FDMA systems are economically more viable for a low number of users. The DTU systems are expected to contain as many as 10,000 terminals; hence the TDMA communications technique is recommended.

c. Based on a 1000 terminal network, about three-fourths of the system cost is required by the terminal segment and one-fourth for the satellite segment. Thus performance/cost optimization of the terminal is of key importance.

d. It is expected that a TDMA terminal will cost about $518,000 and that an FDMA terminal will cost $668,000. These terminals could simultaneously accommodate 10 channels at 64 kb/s, one channel at 1.5 Mb/s, and one channel at 6.3 Mb/s.

e. It is recommended that user terminal antennas not exceed 5 meters in diameter in order to maintain low cost manufacture and installation. A variable power transmitter reduces the outage period associated with heavy rainfall.

f. An increase of spacecraft power from that of the baseline design is not cost effective because the communications is uplink limited; more spacecraft power only helps the downlink.

g. Techniques to provide a variable link capacity per coverage beam are recommended in order to effectively match the consumer traffic demands. Variations to modify the equal capacity baseline concept include variable baseband switch interconnect time, nonuniform burst rate per beam, and allocation of additional transponder channels to the high user density beams.

h. A 25-beam spacecraft that provides overlapping coverage of all of CONUS is feasible. Baseline spacecraft power of 25 W rf per beam leads to spacecraft configurations that will require about one-third the length of the Shuttle Orbiter payload bay.

i. Demodulation to baseband, baseband switching at a nominal rate of 750 reconfigurations per second, and remodulation in the spacecraft are recommended in order to enhance link performance and remove the need for sophisticated onboard frequency synthesizers.

j. The equivalent allocated circuit costs of DTU service are dependent upon many assumptions concerning costs of financing, inflation rates, circuit fill factors, etc. One estimate of the costs (neglecting inflation) for a full capacity system is $3700 per year per 64 kb/s channel, $74,000 per year for a 1.5 Mb/s channel, and $307,000 per year for a 6.3 Mb/s channel. However, these costs are not to be construed as projected tariffs.

1.3.4 Continued Effort

This report evaluates some of the system concepts and the general economic feasibility of 18/30 GHz satcom operation. Recommendations concerning follow-on technology development, continued system studies, and experimental programs are as follows:

a. The matrix of potential operational concepts for satcom systems contains many interconnected paths, as shown in Figure 1.3-1. This report has focused on single-service satellites with uniform traffic demand with emphasis as shown by shading of the figure. It is recommended that the concept analysis phase be continued and expanded to include:
   1. Analysis of combined trunking and DTU service from a single spacecraft.
   2. Hybrid satellites that have cross-connected transponders for operation at C-band, K_U-band, and K_A-band.
   3. Multiple on-orbit satellite configurations such that several communications carriers may share in accommodating user demand.
   4. Additional in-depth analysis of satcom configurations to meet specific communications network requirements.
   5. Studies of consumer demand as function of outage and relative circuit costs.
   6. Additional study of rain attenuation and diversity techniques using data currently collected on U.S. and Japan space programs.
   7. A more detailed examination of spares, operations, and onsite terminal maintenance because of significant system cost impact.

b. The key technology developments have been previously identified. It is recommended that the hardware development program, as currently planned by NASA/Lewis Research Center, be implemented. Additional developments may be required as the study efforts focus on specific design configurations.

c. To verify the critical technology items it is recommended that a Phase II On-Orbit Experimental Test Program be implemented. This will permit evaluation of multiple-spot-beam antenna performance, frequency reuse through spatial and polarization diversity, and outage control during heavy rain periods.

Subsection 2.1

Spacecraft Technology

Table 2.1-1 is a summary listing of the key technology areas for implementing the satellite payload. Subsequent paragraphs examine the various parameter categories in detail.

2.1.1 Multiple Beam Antenna

The multiple beam antenna (MBA) is probably the most critical technology in the implementation of either the trunking or direct-to-user fixed service concepts. The baseline trunking system requires the development of a multiple beam satellite antenna with nominally 58 dB gain at 30 GHz at 3° off axis. Implied in these numbers is an antenna efficiency of 55% and half power beamwidth of about 0.23°. Considerable development work is necessary to achieve this efficiency at 13 beamwidths off axis. An additional challenge is the sidelobe isolation specification, especially for those beams in close proximity (ie, New York and Washington, D.C. beams).

The narrow beamwidth of the antenna generates a pointing accuracy requirement of 0.05° or less. This accuracy is twice as good as that achieved with Intelsat V or INSAT. An RF tracking technique, such as the monopulse technique used on ATS-6 or the Japanese BS, may be required.

The MBA for the direct-to-user (DTU) application is somewhat different than for the trunking system. The DTU MBA beamwidth is about 0.9°. Twenty-five contiguous beams are required for full CONUS coverage with this beamwidth.

A major problem involves the design of the feed. Physical limitations may necessitate the development of a phased array feed assembly instead of the simpler single feed per beam configuration. Isolation between adjacent beams can be achieved by a combination of polarization and frequency channelization. As in the trunking system, a major problem is to achieve a high aperture efficiency off-axis.

Two basic approaches under development are the offset parabolic reflector and the lens antenna. The four-beam offset parabolic antenna being developed for Intelsat V at C-band is typical of the state of the art. A single beam lens antenna with scanning capability over approximately ±5 beamwidths is under development at X-band for the DSCS III satellite.

One of the most promising approaches for a K_A-band MBA is the dual reflector Schwartzschild feed system. Computer analysis indicates that the ±13 beamwidth scan requirement can be met. A prototype antenna should be developed and tested to verify beam steering, gain, and sidelobe performance.

Table 2.1-1. Spacecraft Payload Key Technology Areas

Key Technology Area	System Considerations
Multiple Beam Antenna	Frequency reuse
	Cochannel interference; sidelobe suppression
	Gain, bandwidth, impact on link margin
	Contiguous beam coverage from single reflector
	Off-axis scan efficiency
	Weight
	Aperture efficiency; feed network losses
Receiver Preamplifier	Noise figure, bandwidth, technology maturity, reliability maturity, reliability
Mixer	Bandwidth, dynamic range, system noise temperature, and design flexibility
Filter/Multiplexers	Total system bandwidth
	Guard bands; adjacent channel interference
	Channel bandwidth, group delay and amplitude performance; effect on BER
	IF selection (filter)
	Temperature stability
	Size and weight
	Low insertion loss (multiplexer)
Transmitter	TWT linearity and backoff
	Transmitter reliability
	Solid state amplifier efficiency
	Prime power
	Size, weight, and thermal
	Dual power operation
Switch Matrix	RF vs baseband
	Size, weight, power
	Redundancy configuration
	Switching speed
	Insertion loss
	Isolation
	Synchronization, timing
	Reconfiguration, control
Demodulator/Modulator	Input frequency selection
	Carrier, clock acquisition, tracking
	Bit error rate degradation
	Size, weight, power
	Data rate
	Reliability
	Use of LSI

Table 2.1-1. Spacecraft Payload Key Technology Areas (Continued)

Key Technology Area	System Considerations
Single vs Double Conversion	Low power, size, weight Spurious responses IF selection Impact on transponder size, weight, power, reliability
Time Division Multiplexing	Timing, synchronization Sampling gate width Sampling speed Size, weight, power Reliability
Buffer Storage	Speed (input/output rate) Power Reliability
Gain Control	AGC vs limiting Dynamic range Reliability

In addition, development of a multielement feed is required to generate the multiple beams. The method of coupling the feed array to the various ports, representing different service coverages, must be assessed. This would involve:

a. The feed array layout
b. Design of the radiating apertures
c. Feeding waveguide, including the polarizer and the impedance matching transformer
d. Beamforming and/or switching network with its various millimeter waveguide components such as switches, phase shifters, and hybrids.
e. Coupling between the waveguides and network.

For additional details on the MBA design approach recommended by FACC, see subsection 3.3.

2.1.2 Satellite Receiver

The key receiver parameters for the satellite are noise figure (or temperature) and bandwidth. The lower the noise figure. the less the required ground terminal transmitter power and thus lower terminal costs. However, the satellite antenna temperature is limited to 290 K since it is viewing earth, making the utility of extremely low noise receivers in the satellite (less than 3 dB noise figure) of minimal value.

The simplest approach is to take the received (30 GHz) signal from the antenna and convert it to some lower intermediate frequency for which space-qualified, low-noise, wideband, solid-state amplifiers are available. This was done in the Japanese CS, where a balanced low-noise mixer was driven by a 26 GHz local oscillator to downconvert the incoming signal to 4 GHz. A noise figure of 8 dB was achieved with a bandwidth of 2 GHz. A 4 GHz IF for the FDM configuration would be somewhat more difficult because of the increased system bandwidth and the added requirements this puts on the filter multiplexers.

IF amplifier noise figures of about 2 dB have been obtained for frequencies up to 4 GHz using GaAs MOSFETs with 1 μs gate lengths. Advances in Schottky-Barrier diode technology, particularly in GaAs, have made available mixer diodes with high cutoff frequencies (800 GHz at 0 V bias) and low junction capacitance (0.1 pF) with mixer conversion losses of less than 5 dB in the K_A-band frequencies. Potential reductions of the mixer conversion loss and noise figure of single sideband (SSB) mixers of approximately 2 dB are possible through the use of image enhancement mixers, that is, mixers that employ proper reactive terminations of the image frequencies to enhance the noise figure. Reported results of image enhancement mixer/IF amplifiers operating at 35 GHz using laminate-mode waveguide technology demonstrate SSB noise figures of 5.8 dB (3.1 dB conversion loss, 2 dB noise figure (NF) of 1.2 GHz IF amplifier, and 0.7 dB filter loss). However, careful assessment of technology maturity, implementation problems, and reliability must be made before serious consideration is given to this approach.

Bell Telephone Laboratories has done some experimental work on a low noise 30 GHz receiver consisting of a local oscillator and downconverter built on a silica substrate using hybrid integrated circuit techniques. The 28.4 GHz local oscillator source is a Gunn diode and the mixer a beam-leaded Schottky-barrier diode. A single sideband noise figure of 5.5 dB at 30 GHz was achieved, including a 0.8 dB contribution of the IF amplifier. The usable bandwidth was approximately 700 MHz.

However, downconverting initially in a low noise mixer has a number of disadvantages in comparison with the use of an input low noise preamplifier. First, it is more difficult to achieve a low transponder system noise temperature when inputting directly to a mixer. This is because without the input gain of the preamplifier stages, conversion loss of the mixer system insertion losses and the noise figure of subsequent gain stages become much more significant in determination of the overall transponder system noise temperature. An additional important consideration is that this severely limits flexibility in the receiver design and layout, since placement of the mixer and intervening losses become more critical in a direct downconversion system. Mixer bandwidths and dynamic range are also limitations in the present technology.

On the other hand, in application of a low noise amplifier, the gain and noise figures achievable, maturity of present technology, and qualification status are all concerns in the present technology.

It is of particular significance in tradeoff studies that low noise amplifiers have been built at lower frequencies utilizing tunnel diode amplifiers (TDA), field-effect transistor (FET) amplifiers, and parametric amplifiers. Potentially, the FET is far superior to the TDA in terms of its inherent stability, greater bandwidth, higher linearity, and superior reliability. Particularly the FET amplifier's characteristics of gain, low noise figure, stability, wide bandwidth, and reliability make it an attractive candidate for low noise front end receiver applications. Recent FET developments have extended the high frequency limit, bringing the FET to within striking range as a viable condidate for 30 GHz operation. The most recent demonstrated performance of low noise FETs includes 2.5 dB NF devices with 7 dB associated gain at 18 GHz. Kumn of Hughes Aircraft Corporation has reported noise figures of 4 to 5 dB at 30 GHz using 0.5 μs devices and with even better NFs projected for 0.25 μs devices. It is of particular significance in tradeoff studies that the achievement of a 5 dB NF at 30 GHz would provide approximately 2 dB improvement in the satellite transponder system noise figure over a mixer/IF amplifier design.

Although the parametric amplifier shows promise of achieving the performance desired at 30 GHz, there are a number of critical limitations to its employment for FDM satellite applications. At present, low noise figures appear to be easily achievable. However, attaining the necessary wide bandwidth performance is difficult. The parametric amplifier also suffers from stability problems, the need for a high frequency pump source, and the difficulty of effecting a space qualified model.

Another important consideration is the selection of a single conversion or dual conversion transponder design. The simplest and most straightforward design would be a single conversion system. This also has an advantage in terms of percentage bandwidths. However, these advantages must be weighed against lower noise figures achievable with a lower IF, higher filtering *Q*s, lower circuit losses, and relative ease in achieving gain, amplitude, and group delay performance.

Since transponder size and weight are always paramount, transponder designs will use as much microwave integrated circuitry as possible. Particularly, recent advanced technologies developed for Intelsat and INSAT can be used to minimize overall transponder weight.

2.1.3 Signal Routing

A multiple-beam satellite requires means for interconnecting the various receivers and transmitters to match the traffic requirements. This interconnection can be controlled by a switch matrix.

Two classes of switching are considered — rf (IF) switching and baseband switching. For a K_A-band satellite, the signal would probably be downconverted to an IF of 4 to 12 GHz, switched, and upconverted.

Considerable interest exists in switching matrices for SS-TDMA applications, as shown in Table 2.1-2. It is expected that the state of the art in this field will advance rapidly during the next few years.

Table 2.1-2. Users and Proposed Users of Matrix Switches for SS-TDMA in Communication Satellites

Number of Ports	User/Proposer	Comments
2 x 2	H - SAT/ESA	Experimental European satellite now under study
4 x 4	Hughes	Waveguide X - band ferrite system
4 x 4	TDRS/Western Union	Under construction for space use
4 x 4	FACC	Studied using dual gate FETs
4 x 4	Intelsat/FACC	Under consideration for SS - TDMA trials in Intelsat V
4 x 4	Fujitsu Labs	Digital switch for television
8 x 8	KDD - Japan	Experimental
8 x 8	Hughes	Experimental using single gate FETs
8 x 8	Intelsat	Under consideration - G. Dill
16 x 16	Intelsat/Comsat	Switch developed by Thomson - CSF
16 x 20	Sanders Associates	For aircraft systems
18 x 18	Comsat	Proposed by W. Morgan
20 x 22	Sanders Associates	For aircraft systems
40 x 40	FACC	Studied by Cuccia, Davies, and Matthews
40 x 40	Lincoln Labs	Studied by W. Morrow
846 x 846	Aerospace	Studied by I. Bekey for electronic mail
634 x 1491	Aerospace	Studied by I. Bekey for educational TV

RF Switching

Requirements for an rf switch matrix are listed in Table 2.1-3. The rf bandwidth of 2.5 GHz, required for the trunking FDM configuration, probably dictates an IF of 12 GHz.

Table 2.1-4 lists the types of high speed devices that might be considered for RF switching matrices.

Table 2.1-3. Requirements for an RF Switch

1.	Transfer time preferably less than 1 μs.
2.	Delay variations over the relevant frequency band less than 0.5 ns.
3.	Frequency response within 0.1 dB over the relevant frequency band.
4.	Reflection loss 30 dB or better over the relevant frequency band.
5.	Isolation better than 80 dB.
6.	Insertion loss preferably in the region of 0.1 dB.
7.	Low dribble voltage and small switching transients.
8.	Essentially infinite life and maintenance-free operation.
9.	Bandwidth (for 18/30 GHz application) of 2.5 GHz.

Table 2.1-4. Types of High Speed Switching Devices

Type	Switching Speed Capability	Remarks
PIN Diode Switch:		
• Series	1 - 5 ns	Used in SPNT switches.
• Shunt	0.7 - 5 ns	Used in path length modulators or variable attenuators.
• Lowpass Filter with Varying Cutoff	10 - 50 ns	Used in Rozet matrix.
Varactor Diode - Shunt	0.5 - 10 ns	Requires large tuning voltage to tune a circuit around a Smith chart not suitable as a direct on-off device.
Schottky-Barrier Diode	0.5 - 5 ns	Widely used in quad-diode system in doubly balanced modulators.
Bipolar Transistors:		
• Saturated	100 ns or greater	Used in TTL logic.
• Nonsaturated	0.7 - 50 ns	Used in ECL high speed logic.
Field Effect Transistors:		
• JFET	$<$ 200 ps	Used in gigabit logic.
• GaAs MOSFET Single Gate	0.5 - 1 ns	Used for microwave frequency RF switches. Requires low switching voltage.
• GaAs MOSFET Dual Gate	0.2 - 2 ns	Used for microwave frequency RF switches with gain control for up to 5 Gb/s.
Transferred Electron Devices (TEDs)	$<$ 20 ps	Used in experimental 5-10 Gb circuits.
Josephson Tunneling Devices	$<$ 10 ps	Capable of up to 10 Gb/s.

Comsat Labs started development of a switch matrix in 1973. This was followed by a 16 x 16 switch matrix development to Thomson-CSF and a distribution control unit to Intertechniques, both in France. At the same time, work was started on an 8 x 8 switch matrix in Japan at KDD and at TRW under an AT&T contract. These switches operate at 4 GHz, which could be the IF of an 18/30 GHz transponder.

Switches in spacecraft are by no means new. FACC has logged hundreds of thousands of hours of operation in space of special SP2T and SP4T PIN diode switches to despin the UHF antenna of the SMS satellites and the ATS-6 satellite.

The splitter-combiner switch matrix of Figure 2.1-1 interconnects sets of splitters and combiners to provide the capability of interconnecting any one of N inputs to N outputs. The power splitters and combiners can use Wilkinson techniques, since each splitter handles the same signal to its output ports, while the combiner will only have one signal input at a time.

Figure 2.1-2 shows the KDD switch matrix using B-element switches, which provide transmission in either of two states (developed at KDD Laboratories in Japan). Figure 2.1-3 shows the function of a B-element switch. This switch can be realized using 8 PIN diodes, which provide 14 dB transmission loss and 40 dB isolation loss over the 3.7-4.2 GHz band.

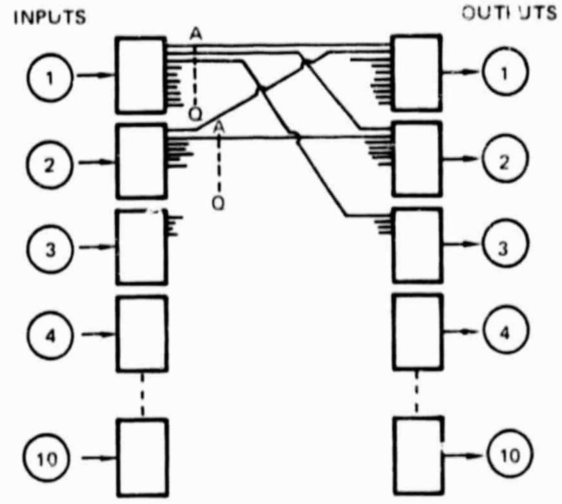


Figure 2.1-1. Matrix Switch Using Splitter Combiner Circuits

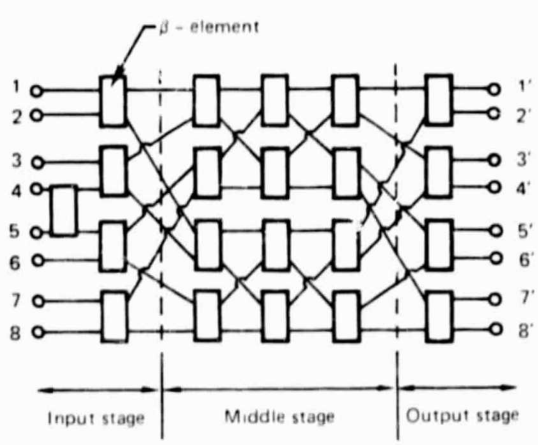


Figure 2.1-2. Rearrangeable Multistage Matrix Using B-Elements

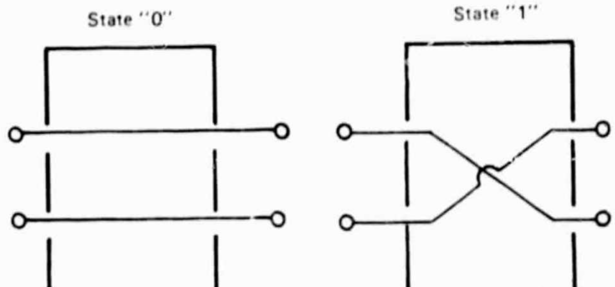


Figure 2.1-3. Function of B-Element Switch

The Advanced WESTAR K_U-band communications payload contains a 4 x 4 switch matrix. This switch utilizes 12 PIN diodes in a series-shunt ring configuration. This configuration enables simultaneous achievement of both isolation and switching speed requirements. The characteristics of the switch matrix are listed in Table 2.1-5. A preliminary reliability assessment was made, and the predicted failure rate is 1780 failures for 10^9 hours. (Reference: R. P. Liccini, TRW Defense and Space Systems Group.)

Table 2.1-5. Advanced WESTAR 4 x 4 Switch Matrix Characteristics

Parameter	Objective	Performance
Frequency (GHz)	2-4.5 GHz	2-4.5 GHz
Insertion loss	3.5 dB	3.5 dB
VSWR	1.5:1	1.4:1
Isolation	60 dB	65 dB
Switching time	< 75 ns	50 ns
Dc power	< 10 W	8.2 W

Baseband Switching

A baseband switch matrix could be used in a repeater satellite which demodulates the incoming signals. A baseband switch matrix promises less size and weight and lower power requirement than the equivalent RF switch matrix.

One approach uses junction FET switches and low power CMOS logic in a transmission line to obtain a 25 x 25 connecting network with video bandwidths approaching 500 MHz. (See Figure 2.1-4.) Ac coupling is recommended, necessitating a minimum number of data transitions per second. The strip transmission line would be fabricated on a G10 epoxy glass substrate 0.125 inch thick. At a data rate of 150 Mb/s, the stripline would be 0.025 inch wide and $0.7N$ inch long, where N is the number of lines to be switched.

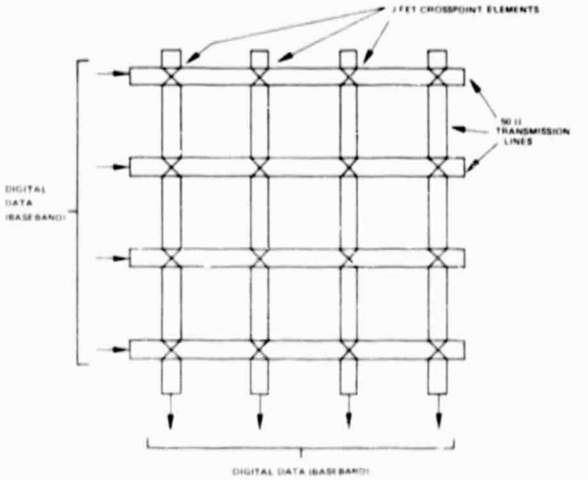


Figure 2.1-4. Digital Baseband 4 x 4 Connecting Network (Nonblocking)

Switching speed of 1 μs and isolation of 40 dB is readily obtainable up to 300 Mb/s input rates. Table 2.1-6 summarizes key parameters.

The requirements for a baseband switch are listed in Table 2.1-7. Rapid advances are being made in the development of high speed digital logic suitable for implementing these switches. The main candidates are devices using silicon-on-sapphire and GaAs technology. Table 2.1-8 compares these two technologies.

Table 2.1-6. Parameters of Baseband Switching Matrix Using Junction FET Switches

Matrix	Weight (kg)	Size (in ^{3})	Power (W)
16 x 16	2.0	40	8
25 x 25	2.6	100	13

Table 2.1-7. Requirements for a Baseband Switch

1.	Transfer time preferably less than 1 μs.
2.	The degree of amplitude linearity high enough and the intrinsic noise low enough to give an NPR of 72 dB or better at maximum loading of the system, irrespective of the position of the switch in the system.
3.	Phase and frequency response such that the transmission of a TV test signal will conform with the CCIR recommendations for 625 lines monochrome and color.
4.	Reflection loss over the relevant frequency band better than 30 dB.
5.	Isolation over the relevant frequency band better than 80 dB.
6.	Insertion loss preferably in the region of 0.1 dB.
7.	Low dribble voltage and small switching transients.
8.	Essentially infinite life and maintenance—free operation.

Table 2.1-8. IC Device Technology Projections

Parameter	Pilot Production Capability			
	1979		1985	
	Silicon	GaAs	Silicon	GaAs
L = feature size (microns)	2 to 4	1 to 2	0.5 to 1	0.25 to 1
G = gates/chip (maximum)	10,000	50 to 100	100,000 to 500,000	5,000 to 10,000
Chip size (mils)	250	50	300 to 400	200
F = LSI clock frequency	10 to 75 MHz	1 to 2 GHz	50 to 250 MHz	3 to 5 GHz
F_{MAX} = maximum ic circuit Frequency	1.5 GHz	10 GHz	5 GHz	25 GHz
M = throughput function per chip (gates x MHz)	10^5	10^5	2×10^7	2×10^7

Comparison of RF and Baseband Switch Matrices

The weight and power required for both switch matrix types, including control circuits, are shown in Figures 2.1-5 and 2.1-6. The figures clearly show the potential advantage of baseband switching over rf switching, especially when the number of switching ports is large.

On the other hand, baseband switching requires more development, especially for the satellite demodulator/remodulator. For this reason, rf switching will be used when the number of beams to be switched will be small (less than 10).

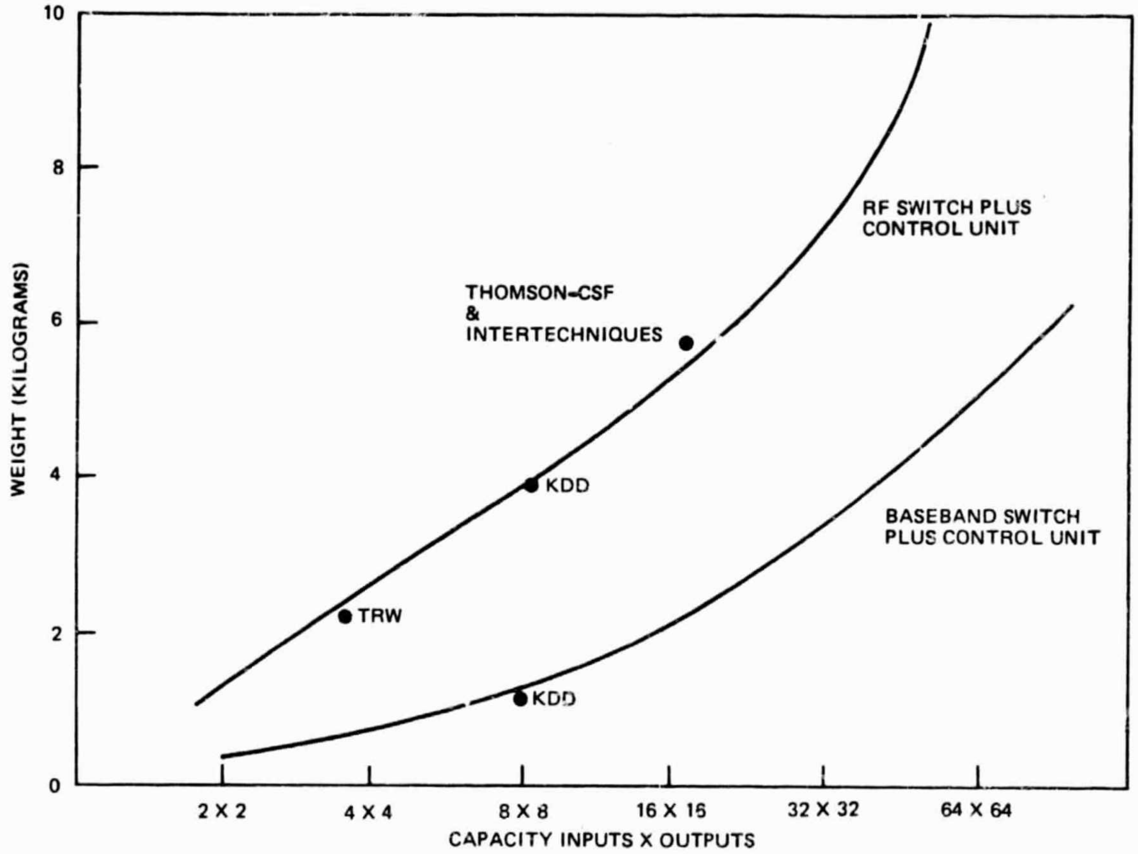


Figure 2.1-5. Weight Versus Capacity for Matrix Switch and Controlling Circuits

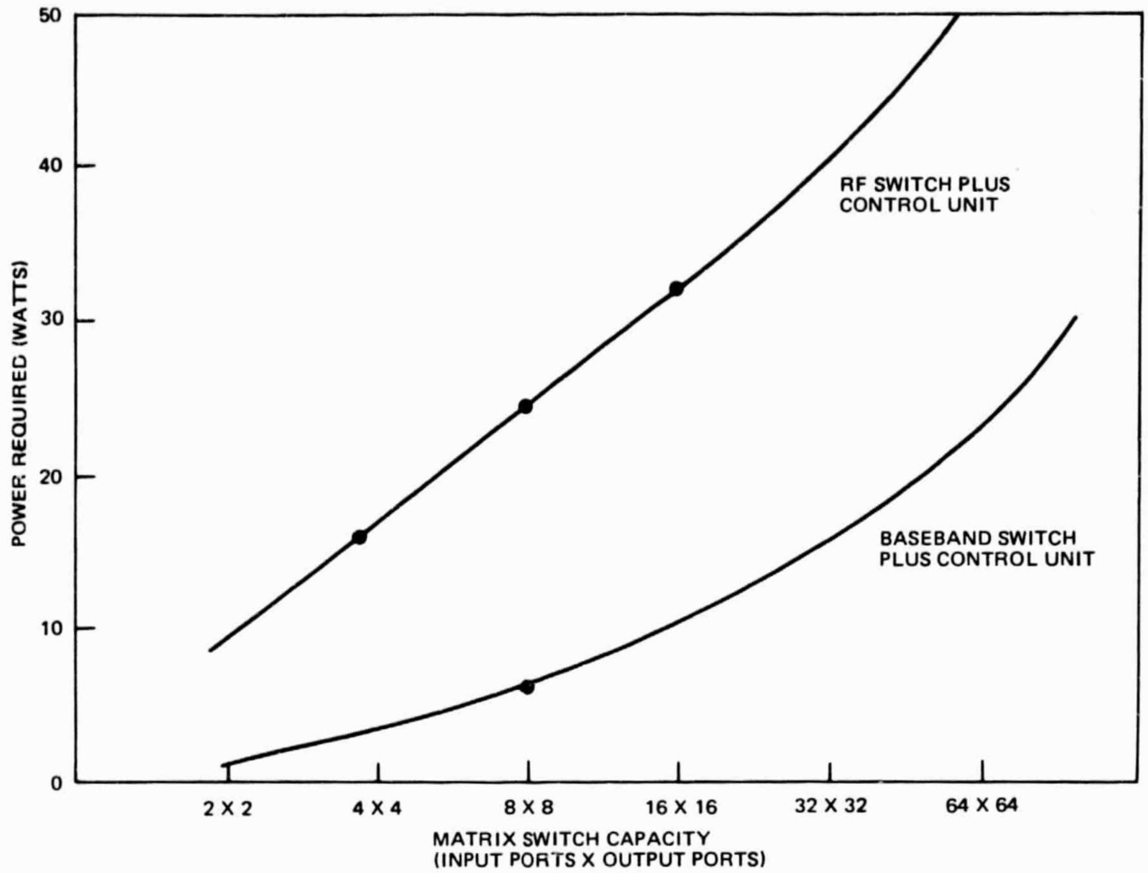


Figure 2.1-6. Power Required to Operate Matrix Switch as Function of Switch Capacity

2.1.4 Transmitter

Some important considerations that must be taken into account in a transponder design are:

- TWTA vs solid state amplifier
- TWTA linearity and backoff
- Solid state amplifier efficiency
- Prime power requirements
- Dual power mode operation
- Size, weight, and thermal control

Table 2.1-9 lists the status of power amplification for communication satellites at 18 GHz, as of December 1978. Figure 2.1-7 provides a projection of power output availability at 18 GHz up to 1984.

Table 2.1-9. Power Amplification for Communication Satellites at 18 GHz (December 1978 Status)

Type of Amplifier	Power Level	Comments
TWTA - helix	2.5 W 4 W 10 W	Used in ATS - 6 Used in Japan CS Developed for H-SAT
TWTA - coupled cavity	No activity at 18 GHz for space - potential for 50 - 200 W	Up to 700 W at 11 GHz, 200 W under development at 43 GHz
FET amplifiers	1 W achieved 2 W objective	Significant activity in FET development due to terrestrial radio interests at 15 - 20 GHz
Impatt Amplifiers	1 W 4-5 W	COMSTAR Beacon 5 W developed at 35 GHz by TRW
Gunn amplifiers	0.5 W	Used as medium low noise amplifier

Choice for the power amplifier is presently between a TWTA for high power (more than 0.5 W per unit) and an FET (less than 0.5 W per unit). MCS has an FET capable of delivering 1 W at 18 GHz with an FET. This breakpoint is expected to increase to 2 W at 18 GHz by 1980. It is unlikely in the near term that solid state amplifiers will surpass TWTAs in output power or efficiency.

However, solid state devices offer the potential for orders-of-magnitude improvements in reliability and reductions in size, weight, and voltage requirements. Additionally, the FET amplifier has the advantage in its overall linearity (less backoff).

TWTA technology is available to develop higher power at 18 GHz. A 60 W 16 GHz helix TWTA was developed for use on the shuttle program. Higher power levels (from 100 to 200 W) have been achieved at frequencies of 15 to 40 GHz. These tubes required a coupled cavity instead of a helix. A 5% bandwidth is readily achievable with this technique; 10% can be achieved with some difficulty.

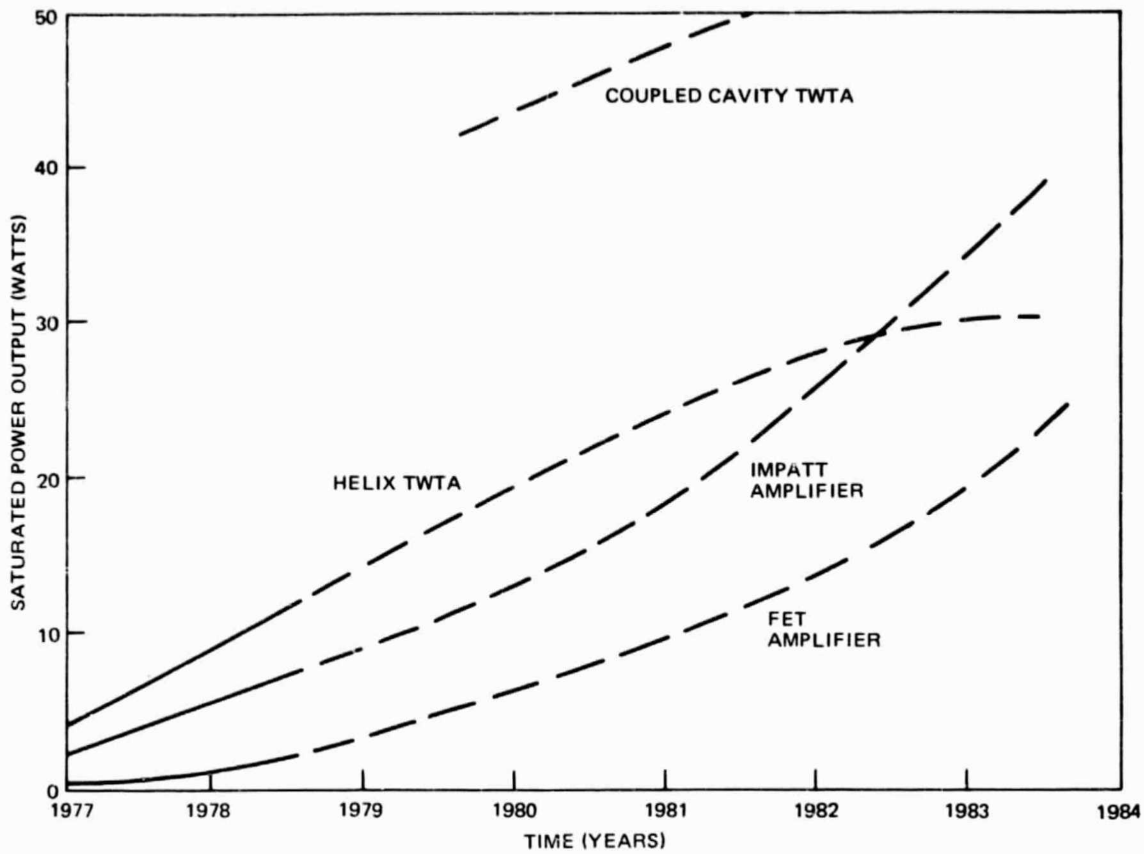


Figure 2.1-7. Projections of Saturated Power Output Levels with Time at 18 GHz for Various Candidate Amplifiers for Satellite Transponders

NASA/Lewis is beginning development of a 75 W 18 GHz multiple power TWTA with a 10:1 power ratio specifically for this application.

Another approach to achieving higher power is to parallel two or more TWTAs. FACC has successfully demonstrated this at 7 GHz with excellent stability in amplitude and phase balance. Possible advantages of this approach are greater distribution of thermal loads and graceful degradation.

Based on the above data, we believe an output power of 400 W could be achieved at 18 GHz with development. However, power output greater than 75 W per TWTA probably is not required.

2.1.5 Frequency Source

The stability required for the satellite local oscillators will be determined by the type of modulation and multiple access technique specified. With proper design, no difficulty is anticipated in meeting requirements using today's technology. For the Japanese ETS-II, for example, FACC (with Marconi) developed a 30 GHz solid-state transmitter for the RLL radio propagation experiment. The spectrum was measured at 30 GHz, and 97% of the unmodulated carrier was found to lie within 150 Hz of the center frequency.

Table 2.1-10 summarizes the principal characteristics of satellite frequency sources now available. Further development appears unnecessary for the types of modulation and data rates now envisioned.

Table 2.1-10. Frequency Standards Review

Type	Short Term (0.1 s)	Temperature	1 Year	Size (In)	Weight (lb)	Power (W)	Info. Source
Crystal	2×10^{-11}	1×10^{10}	3×10^{9} (2)	4 X 4 X 4	1	2	FACC
Crystal (5)	3×10^{-11}	$2.5 \times 10^{11}/25°$ F	3×10^{9}			2 to 3	FE1
Rubidium (3)	2×10^{-11} (1)	1×10^{12}	1×10^{12}	5 X 4.5 X 7.5	10.0	18	Efratrom
Cesium (4)	2×10^{-11} (1)	1×10^{12}	1×10^{13}	5 X 7 X 16	20	20	NRL

(1) Determined by quartz crystal.
(2) Crystal Pre-aging > 2000 hr.
(3) Flew 2 Efratrom standard "ruggedized" units on NTS 1, failed 6-8 months, assumed lamp darkened.
(4) 2 units on NTS 2, Sept. '76. "Easier" to harden than Rb unit.
(5) FltSatCom

2.1.6 Filter/Multiplexer

A key component in most communication satellite transponder configurations is the band-pass multiplexer used to establish the characteristics of the transponder channels and the allocation of available spectrum between channels.

In both the input channel dropping filters and the output combining multiplexer, there are a number of important considerations relative to the transponder design and establishment of the transfer functions. The most significant tradeoffs are:

- Filter/Multiplexer Tradeoffs
- Total System Bandwidth
- Relative Channel Bandwidth
- Group Delay/Amplitude Performance
- Low Loss Output
- Temperature Stability
- Size and Weight

Because of the receiver front end gain, insertion loss of the input multiplexer normally is not a critical factor in transponder design. As a result, odd/even channelization multiplexing can be employed to effect demultiplexing into the relative communication channels. As the total system bandwidth over which the multiplexer must operate is increased, increased difficulties are encountered in obtaining adequate bandwidth for the hybrids or circulators in the demultiplexing matrix. Similarly, a narrow channel presents problems in insertion loss, amplitude variation, and stability, while too wide a bandwidth again presents moding, rejection, and flatness problems. Thus, an important tradeoff relative to an input multiplexer involves selection of single conversion versus dual conversion. Demultiplexing at a lower IF is advantageous in terms of ease in achieving group delay and amplitude performance as well as effecting higher Q and lower losses in the filters. However, the relative percentage bandwidths of both the wideband data as well as the demultiplexed channels is increased as the IF is reduced, thereby increasing the multiplexer difficulty. Careful assessment of these tradeoffs must be made in future transponder designs, particularly those using an FDMA transponder configuration.

The design of the 18 GHz output multiplexer is particularly critical in those configurations where a large number of narrowband transmitters are connected to a single antenna part. The insertion loss is especially important since this directly affects the radiated power (EIRP). In the Japanese CS Program, four-port circularly polarized TE_{11} cylindrical mode filters were used both at 30 and 20 GHz for the input and outut filters. The insertion loss of the output multiplexer varied between 0.95 and 1.15 dB. The filter consisted of four 182 MHz 0.01 dB ripple Chebyshev sections in tandem.

On Intelsat V, contiguous output combining multiplexers at 4 GHz are used on the output instead of the conventional odd/even multiplexers. Using the multiplexers, all adjacent channels can be summed on a common manifold with only minimal guard bands, thereby eliminating an antenna or an extra feed polarization. Although such a multiplexer has much more complexity, there is considerable overall satellite wieght savings in terms of the multiplexer itself compared to two odd/even multiplexers, and there is also the potential elimination of an antenna. The relative performance tradeoffs and technical risks of a contiguous multiplexer at 20 GHz needs to be carefully assessed.

2.1.7 Demodulator/Modulator

A key technology to be investigated is the satellite demodulator and modulator for use in those transponder configurations requiring baseband switching, buffer storage, and/or format conversion. Considerable work is underway on the development of a demodulator for DPSK switch for satellite application. In particular, Nippon Electric Company is developing a 120 Mb/s DPSK demodulator for Comsat Labs that converts the 6 GHz input signal directly to baseband, thus eliminating need for a separate local oscillator chain and downconverter. Design goals include weight of 1.8 kg maximum and primary power requirement of less than 7 W.

The chief disadvantage in using DPSK is the 2 to 1 increase in rf bandwidth required, relative to QPSK. DQPSK is undesirable because at least 3 dB more power is necessary in

the uplink to maintain a specified BER. Therefore, it is recommended that attention be directed to the QPSK demodulator.

Three basic demodulator concepts are (1) carrier reconstruction with a x4 loop, (2) Costas-loop demodulator, and (3) carrier generation by modulation of the input signal by a locally generated replica of the input signal. While these demodulators are more complex than the DPSK demodulator mentioned above, it is believed that they will be feasible for satellite use in the mid-1980s. This optimism is based largely on the rapid development of high speed analog and digital LSI using GaAs and SOS technology. Experiments in several laboratories have demonstrated feasibility of achieving 500 Mb/s or more speeds with relatively low powers. At least one laboratory has demonstrated a Costas-loop demodulator using GaAs LSI technology.

Other than feasibility, the critical issues are power consumption and reliability.

Subsection 2.2

Earth Terminal Technology

The key technology areas considered for the earth terminals are listed in Table 2.2-1 and examined in this subsection.

The cost of the user terminals is a major factor affecting the viability of the direct-to-user (DTU) concept. Use of existing technology leads to a unit procurement cost of $400,000 to $600,000 per terminal. Clearly, the requirement exists for development of new technology that can lead to substantial cost reductions in ground terminal components.

Reduction of operational and maintenance costs is also a significant factor in the overall DTU system costs. Methods for achieving reliable operation with unattended operation and an acceptable MTBF and MTTR need to be considered.

2.2.1 Antenna Subsystem

The antenna subsystem consists of the reflector, the feed, the pedestal, and the antenna pointing control equipment. Key parameters are antenna pointing accuracy, reflector surface tolerance, and power handling capability of the feed.

The accuracy of a reflector surface and the environment under which that surface must be maintained have a tremendous influence on the performance and cost of an earth terminal, especially when K_A-band frequencies are handled. Figure 2.2-1 shows the expected loss of directivity for an antenna as a function of its rms surface tolerance. It is apparent that the standard microwave tolerances of 0.8 to 1.1 mm are inappropriate for millimeter waves because losses exceed 3 or 4 dB for 30 GHz. At this frequency over half of a normal reflector surface area is made ineffective by its roughness and could be eliminated if the accuracy could be improved to better than 0.4 mm. The tradeoff, then, is not just one of performance but one of weighing the rate of cost increase as the surface is improved against the rate of cost decrease as the area is reduced.

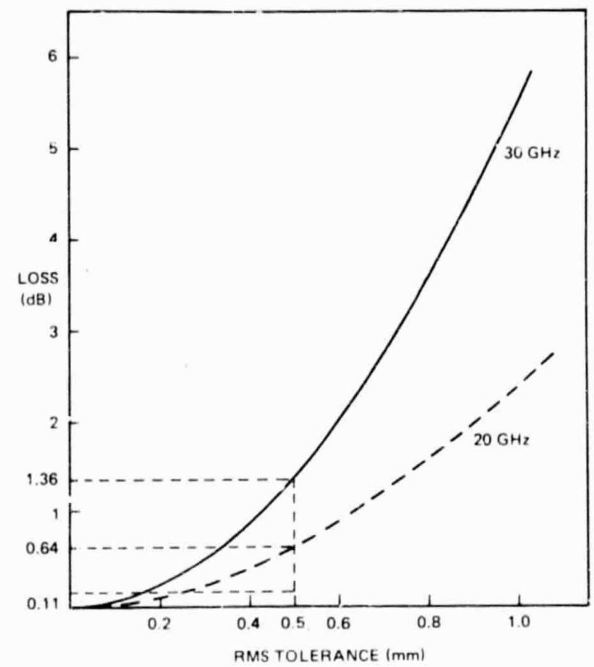


Figure 2.2-1. RMS Surface Loss

Ford Aerospace & Communications Corporation

Table 2.2-1. Earth Terminal Key Technology Areas

Key Technology Areas	System Considerations
Antenna Subsystem	Aperture efficiency Surface tolerance Pointing accuracy - steptrack vs monopulse Feed losses, diplexer
Receiver	Noise figure, bandwidth Need for redundancy
Transmitter	Cost Bandwidth Saturated vs linear, number carriers transmitted Output multiplexer Need for redundancy Variable output power, high power during rain High peak power, low duty cycle for TDMA DTU application
Modem	High data rates Carrier, clock acquisition, tracking Equalization Cost
Data Handling	Multiplexing Buffer storage Timing Network interfaces
Diversity Switching	Signal quality measurement Switch speed, delay compensation. Bit integrity

It is also important to note that the larger the aperture the more difficult the surface is to control. A typical curve illustrating this problem is shown in Figure 2.2-2.

Power handling in the antenna feed is another parameter that must be controlled. Minimal problems exist for the level of power available today in existing HPAs. However, the power dissipated in the antenna feed increases as power requirements go up. Since the waveguide components are extremely small and lossy at K_A-band, cooling of these components is a potential problem.

Other parameters that must be controlled are diffraction, blockage spillover, and other normal parameters. These, however, are not unique to K_A-band and within reason are controllable parameters. The cost of the antenna will have a breakpoint where cooling (liquid) is required in the feed.

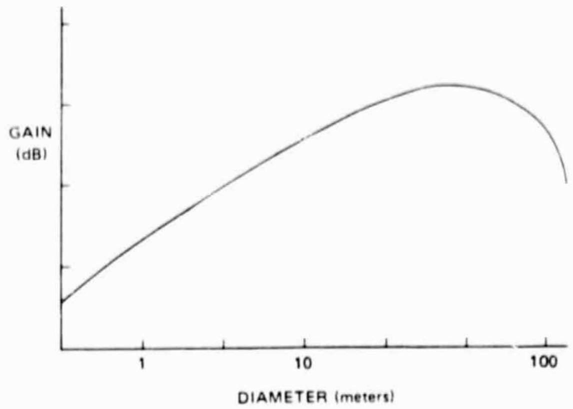


Figure 2.2-2. Antenna Gain Versus Diameter for Specified Surface Tolerance

As pointing accuracy increases, the rigidity of the structure increases and, therefore, the cost increases. The rigidity of the structure is also impacted by the type of environment in which the antenna must operate. For example, the type of material in an antenna in Maryland would not be the same as an antenna in Fairbanks, Alaska. FACC has performed studies of wind effect on antennas in the area of rf performance and pointing and has an excellent data base on antenna structures of all sizes. [Ref: Luik and McCulloch, "Windscreening Effects on Antenna Tracking Performance," AIAA Paper 76-298, presented at AIAA/CASI Sixth Communications Satellite Systems Conference, April, 1976.]

For the trunking system, the beamwidth of the 12 m earth terminal antenna is only 0.06° at 30 GHz. The Japanese antenna is designed with multimode antenna feed and a single channel tracking receiver at 18 GHz designed to achieve a tracking accuracy better than 0.01° rms, leading to a pointing loss of less than 0.4 dB.

To reduce earth terminal costs for the DTU application, an earth terminal optimization study might be conducted to perform the following:

a. Optimize reflector, feed, and pedestal design to minimize manufacturing costs.

b. Optimize steptracking parameters for reduced tracking errors and cost.

c. Investigate unattended operation with remote sensing of terminal parameters. Consider switching of redundant equipment by remote control. Compute MTBF and MTTR for redundant and nonredundant configurations to determine link availability versus cost trade.

d. In a TDMA system, a major cost item is the timing equipment. Precise measurement of path length to the satellite is necessary. A significant cost reduction may be achieved by developing a simplified algorithm that computes the path length at each terminal using a low cost microcomputer. It has been estimated that an accuracy of

0.1 μs may be achieved using this technique. A harmonic series is used with 12 to 14 coefficients computed at a central computer site for each terminal. These coefficients are updated and transmitted to the user once a week.

e. Investigate methods of reducing the cost of generating 20 and 30 GHz local oscillator signals.

2.2.2 Receiver

The key receiver element is the low noise amplifier (LNA). In the past year, GaAs FET noise performance has continued to improve at frequencies above 10 GHz. For example, a room temperature noise figure of 2.3 dB with associated gain of 7 dB was recently obtained at 18 GHz from a GaAs FET with 0.5 μs gate length. Cooled to 77 K, the device yields a 1.2 dB noise figure with 10 dB gain. The key parameters that enable such remarkable noise performance are high mobility at the interface between active layer and substrate, short channel length, minimum parasitic capacitance between gate and source, and low gatemetal resistance. [Ref. C.A. Liechti, "GaAs Technology: A Look Into the Future," *Microwaves,* October 1978, pp. 44-49).]

Bipolar transistors are limited to about 6 GHz. Parametric amplifiers give noise performance of 200 K uncooled, 50 K cooled, but the required 2.5 GHz bandwidth requirement is difficult to meet, and cost and complexity are high.

It appears that the GaAs FET LNA will satisfy the K_A-band earth terminal requirement in the 1980-1990 period.

2.2.3 Transmitter

The major issue for the DTU terminal is the feasibility of the high power amplifier (HPA) required to overcome rain fades up to 15 dB. Powers in the order of 1 kW are required at 30 GHz. An 800 W air-cooled TWTA has been developed by the Japanese, and Raytheon has built a liquid-cooled 1 kW TWTA for 36 GHz.

It may be desirable to parallel two lower power HPAs to obtain the desired output power. In this case, only one HPA is operated except during heavy rainfall. Thus full redundancy is provided up to a 12 dB fade.

The largest single item of cost is the HPA, estimated to be over $100,000 each. Development of HPA technology at 30 GHz to reduce production costs is required to make the DTU concept cost effective. The gyrotron may be one answer since large powers can be generated without the need for maintaining extremely close dimensional tolerances. Practical devices are now under development at the Naval Research Laboratories and at Varian Associates. While this work is aimed at obtaining 10 kW CW in the 30-40 GHz range, the design might well be suited for lower power outputs.

If a TDMA uplink is used in the DTU system, the required HPA peak power will be higher than that required for an FDMA uplink. It may be possible to take advantage of the low duty cycle of the TDMA burst in designing the HPA power supply and cooling system. The gyrotron may be well suited for this application.

The uplink requirements dictate the need for controlling HPA power output by digital command. This is necessary to compensate for rain fades without overloading the satellite receiver or causing cochannel interference in adjacent antenna beams. For the FDMA configurations, it may be necessary to operate the HPA in a linear (backoff) mode to avoid intermodulation interference effects. Alternatively, multiple HPAs coupled into an rf multiplexer could be used. The tradeoffs required to determine the best approach remain to be studied. Considerable development effort is required for the earth terminal transmitter.

2.2.4 Modem

The modem technology for ground based equipment has advanced to the point where data rates up to 1 Gb/s can be readily handled. New developments in GaAs FET devices indicate that a 2.5 Gb/s modem will become feasible by 1982. (Using QPSK modulation, the modem would consist of two 1.25 Gb/s biphase demodulators operating in phase quadrature.) Development of equalizers would also be required.

The principal issue is cost, not feasibility. Effort directed toward simplification of carrier and clock acquisition and tracking circuits will be worthwhile. Development of circuits that can be easily implemented on VLSI chips will greatly simplify maintenance and reduce costs, especially if a significant number of modems is to be produced.

2.2.5 Data Handling

Terrestrial interface equipment is required to span the communication link between the ground station modem and the switching central office of the DTU and instruments. Three classes of equipment are encompassed:

a. Transmission facilities to interconnect the ground station site and the user or switching site

b. Multiplex equipment at either end of this link

c. Conditioning equipment necessary to prepare signals for transmission or multiplexing; for example, analog-to-digital converters, buffer storage, rate converters, and digital data synchronizers.

In addition to simply interconnecting the switch or user to the ground station, this equipment assembles messages or channels for transmission over the satellite links. Therefore, link capacities or network configuration cannot be changed without altering the interconnect equipment. In the past this has been a manual task; in the future it will become automatic or adaptive. Therefore, the monitor and control of the interconnect facility (ICF) will be an important part of the system. Control equipment will increase first cost but will substantially decrease operating costs.

As the data rate increases, buffer capacities and speeds also increase. Buffers are required in all TDMA configurations. In addition, an elastic buffer is required to compensate for satellite motion whenever the satellite link is tied into a terrestial digital network. Otherwise, synchronization cannot be maintained.

2.2.6 Diversity Switching

Space diversity will be required for most trunking applications requiring link availability of 0.999 or higher. Concepts have been advanced for performing the required signal quality measurement and switching functions. However, field demonstration of these concepts at high data rates is needed to verify (1) the reliability and accuracy of the switching function, and (2) ability to preserve bit integrity. The latter function requires a high speed buffer operation to compensate for differences in path delay to the two ground terminals. Development of this buffer and methods for controlling it are required.

A major cost item in a space diversity system is the interconnect link between the two earth terminals. Table 2.2-2 lists the types of interconnects available. At the high data rates expected for trunking systems, multiple channels are required.

Table 2.2-2. Types of Interconnect Systems for Diversity Systems

Type	Channel Bandwidth	Capacity		Relative Cost
		Analog Voice	Mb/s	
Radio Relay 11 GHz 20 GHz	 30-40 MHz 100-400 MHz	 1000-1300 5760 (max)	 60-90 100-400	Least expensive. Equipment presently available at 11 GHz from NEC, Collins, Raytheon. At 20 GHz from NEC, OKI in Japan. Repeaters required every 10-12 miles.
Buried Coaxial Cable	1 Gb/s max per cable	6000 max per cable	400	Digital cable with repeaters available from NEC in Japan and Western Electric in the U.S. Moderately expensive.
Buried Waveguide 40-80 GHz	278-800 MHz bands	10,000 per 800 Mb/s carrier	400-800	In advanced development in Japan, U.S., Europe. Equipment at 800 Mb/s available from Fujitsu in Japan. Most expensive.
Buried Optical Fibers	100-500 MHz per fiber	5000 max	500	In advanced development in U.S., Europe, and Japan. Equipment at rates for T1 and T2 available in U.S. 400 Mb/s equipment available in Japan from Fujitsu, NEC. 24 fiber bundle cable presently being installed by BTL in Chicago for 12,000 voice channels - no repeaters. Moderately expensive, more than buried coaxial cable.

The relative costs of the four systems are dependent on:

a. Data rates on channel bandwidth
b. Distance as it impacts the installation costs of the buried cable/waveguide systems
c. Distance as it impacts the number of repeaters (also a function of data rate) of each of the three systems requiring buried installations.

Further investigation is required, with specific installation constraints, data rate requirements, and terminal separation distances considered.

Subsection 2.3

Rain Attenuation

On an average basis a given location within CONUS is expected to be receiving measurable amounts of rain about 1.5% of the time. During periods of heavy rainfall the satcom signal transmission at 18 GHz and 30 GHz frequency bands will incur a significant attenuation. It is desired to keep the satellite and earth terminal performance parameters low in order to minimize cost; however, the resulting system propagation reliability must be matched to user requirements. A proper understanding of the 18/30 GHz rainfall attenuation effects is therefore one of the most important elements in the determination of viable satcom system configurations.

Analysis of rain attenuation for this report was prepared by Future Systems Incorporated (FSI) under subcontract to Ford Aerospace & Communications Corporation (FACC). The work involved the preparation of a summary of available propagation data collected at 18 and 30 GHz and the definition of link margins required for availabilities ranging from 0.99 to 0.9999. The use of space diversity to reduce the margin requirements was also calculated. The task included the definition of a climatological model of rainfall rates for CONUS. This was needed to define the cumulative time distributions of precipitation attenuation in a concise and manageable form. In performing this study, FSI collected and reviewed a large number of articles, publications, and reports that describe related work.

This subsection summarizes the results of the FSI study.

2.3.1 Propagation Experiments and Attenuation Models

Millimeter wave propagation experiments and corresponding theoretical analyses have been performed for over 30 years. Much of the early effort was devoted to the study of propagation along terrestrial transmission paths. However, many aspects of this work are also applicable to satellite transmission. More recently, propagation experiments along satellite transmission paths have been conducted and are still under way. Much corresponding theoretical work has also been performed.

Some of the theoretical work is concerned with the raindrop size distribution as a function of the rainfall rate and the calculation of specific attenuation as a function of the rainfall rate. Both spherical and oblate raindrops have been studied by various researchers. Experiments of the following categories have been performed:

a. Experiments over terrestrial links
b. Experiments using radiometers
c. Experiments using weather radars
d. Experiments using satellite-borne beacons or transponders

Of these, the experiments using satellites have the most applicability. Measurements made with the following satellites were examined:

a. ATS-V at 15.3 and 31.6 GHz
b. ATS-6 at 13, 18, 20, and 30 GHz
c. CTS (Hermes) at 12 GHz
d. Comstar at 19 and 29 GHz

An empirical model is available to calculate specific attenuation as a function of the rainfall rate (Figure 2.3-1), and this model appears to be generally accepted by most researchers. However, this model is based on uniform rain density over the transmission path, which is not realized in practice. For practical calculation of the total precipitation attenuation along the earth station to satellite transmission path, it was found convenient to postulate an effective path length of uniform rain density. This path length was found to depend primarily upon the rain rate but also upon the frequency and the local climatic conditions. Different models proposed by various groups of researchers and by the CCIR lead to substantial discrepancies, indicating that much further work is needed in this area. The primary differences in the various path length models are (1) the derivation of each from different experimental data and (2) the varying degrees of completeness. Several published expressions for path length are not intended as complete models; hence, discrepancies are likely.

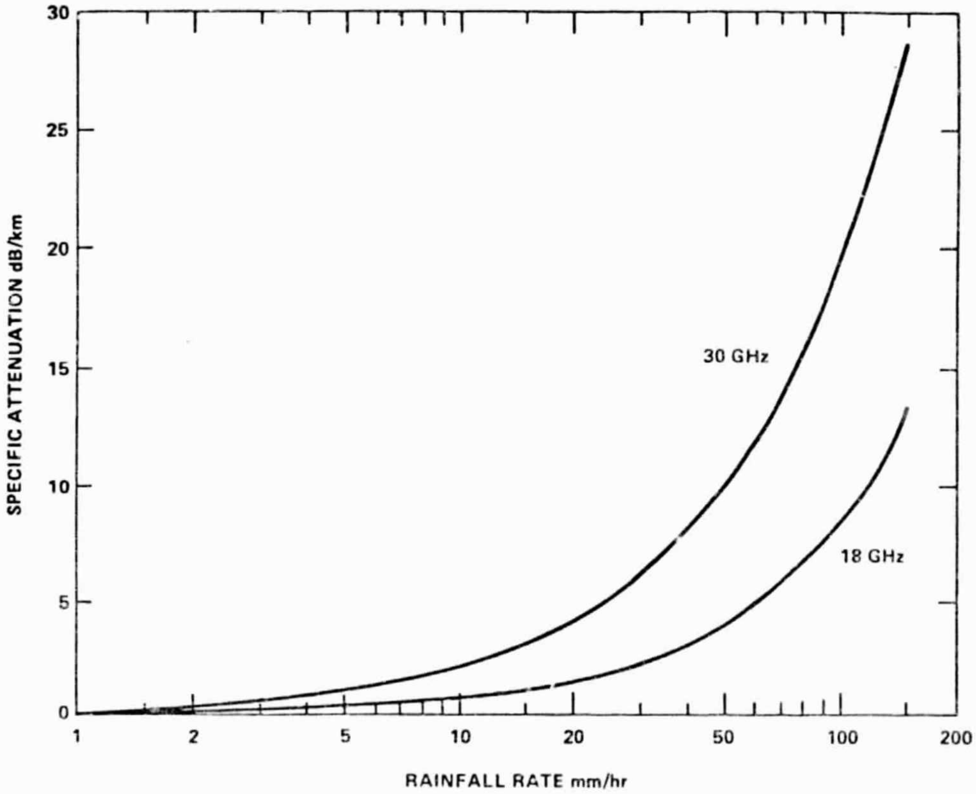


Figure 2.3-1. Specific Attenuation at 18 and 30 GHz as a Function of Rainfall Rate

Typical figures for effective path length as computed using the CCIR model are as follows:

Location	Satellite Longitude	Elevation Angle	Rain Rate (mm/hr)	Effective Path Length (km)
Seattle, Washington	80°W	22°	10	9.5
Chicago, Illinois	100°W	40°	60	5.0

The margins at a given location will vary with varying satellite locations because of the dependence of the path length on elevation angle. As a system design tradeoff, it might be desirable to locate the spacecraft over the eastern United States. Since the Southeast experiences the most occurances of heavy precipitation, the higher elevation angles achieved by this satellite position would reduce margin requirements in this area.

An additional source of degradation on the downlink is the increase in noise temperature caused by precipitation and clouds. This results in an increased system margin requirement. The increase is dependent on the clear-sky system noise temperature and can be expressed as follows:

$$M = 10 \log (T_{sys} + T_{sky})/T_{sys}$$

where

M = increase in margin requirement

T_{sys} = the clear-sky system noise temperature

$T_{sky} = 1\text{-}10^{-A/10}\, T_r$

T_r = the physical temperature of the precipitation, usually about 273 K

A = the excess attenuation over clear sky conditions

Thus, given a system noise temperature of 250 K (a reasonable value at 18 GHz), the increase in margin requirement would approach 3 dB at high values of attenuation and would be less at lower values. Figures given for margins in this report do not explicitly include the noise temperature increase.

2.3.2 Rain Zone Model for CONUS

A large amount of data on rainfall rates is available from the National Weather Service and from various experimenters who have taken precipitation measurements as an adjunct to propagation measurements. Data from both categories have drawbacks:

a. The information presented by experimenters is in the required form of instantaneous rainfall rates, which is required for attenuation calculations. Such data, however, has generally not been collected for sufficiently long periods to permit the construction of a reliable long-term statistical model.

b. The data published by the NWS covers long periods of time; however, rain rates are averaged over longer periods of time so that the instantaneous rain rates are not directly available.

To overcome these problems, transformations have been devised by Rice and Holmberg and others to permit the derivation of the cumulative time distribution of rainfall rates from two quantities: total annual rainfall rate and thunderstorm-to-total-rain ratio. These transformations were found to provide satisfactory results. Based on this information, the rain zone model shown in Figure 2.3-2 havs been developed for CONUS. The model contains six zones, and their rain rate distributions are shown in Figures 2.3-3 and 2.3-4. [Ref: Rice, P.L. and Holmberg, N.R., "Cumulative Time Statistics of Surface-Point Rainfall Rates," *IEEE Transactions on Communications,* COM-21, 1973.]

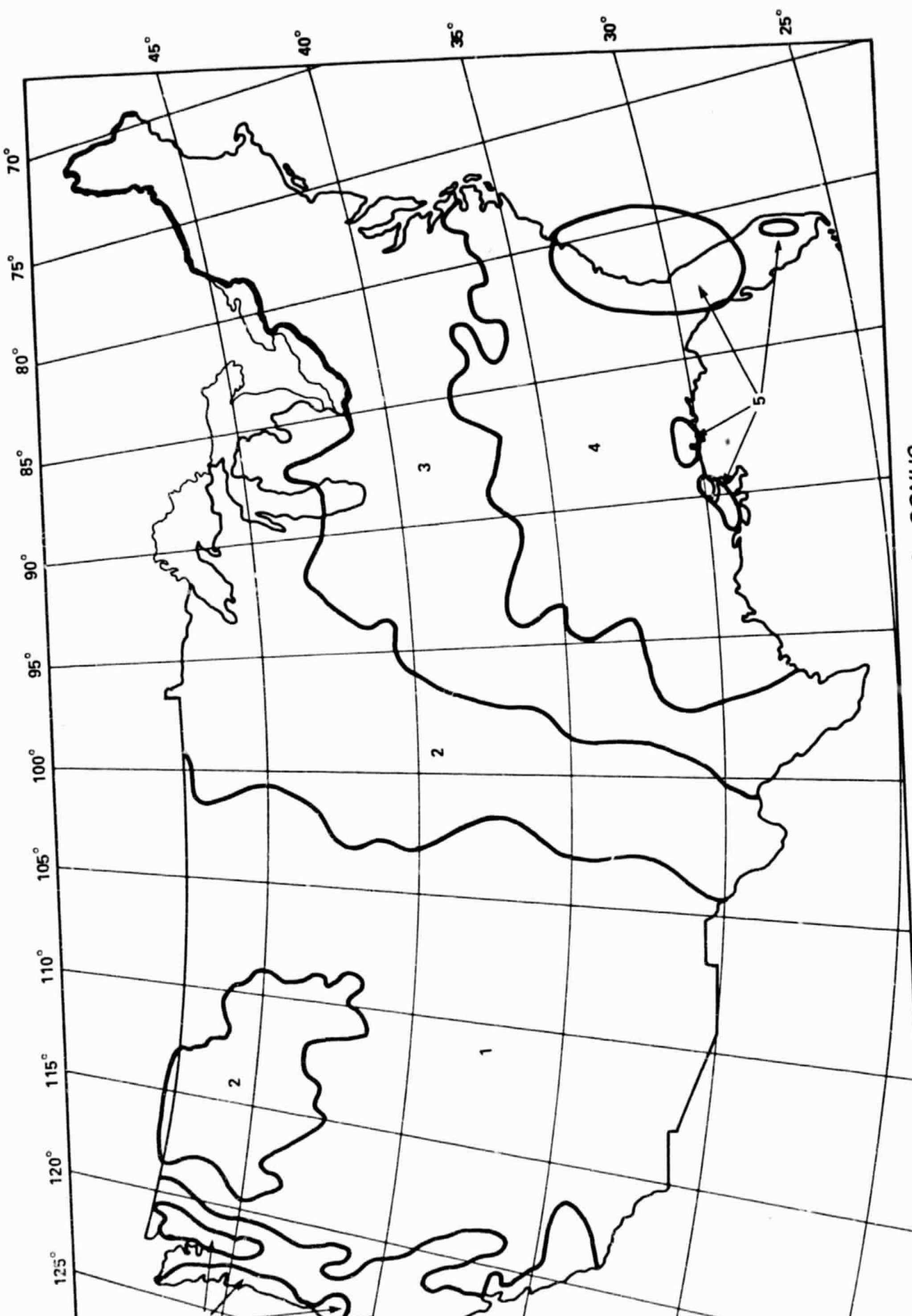


Figure 2.3-2. Climatological Zones for CONUS

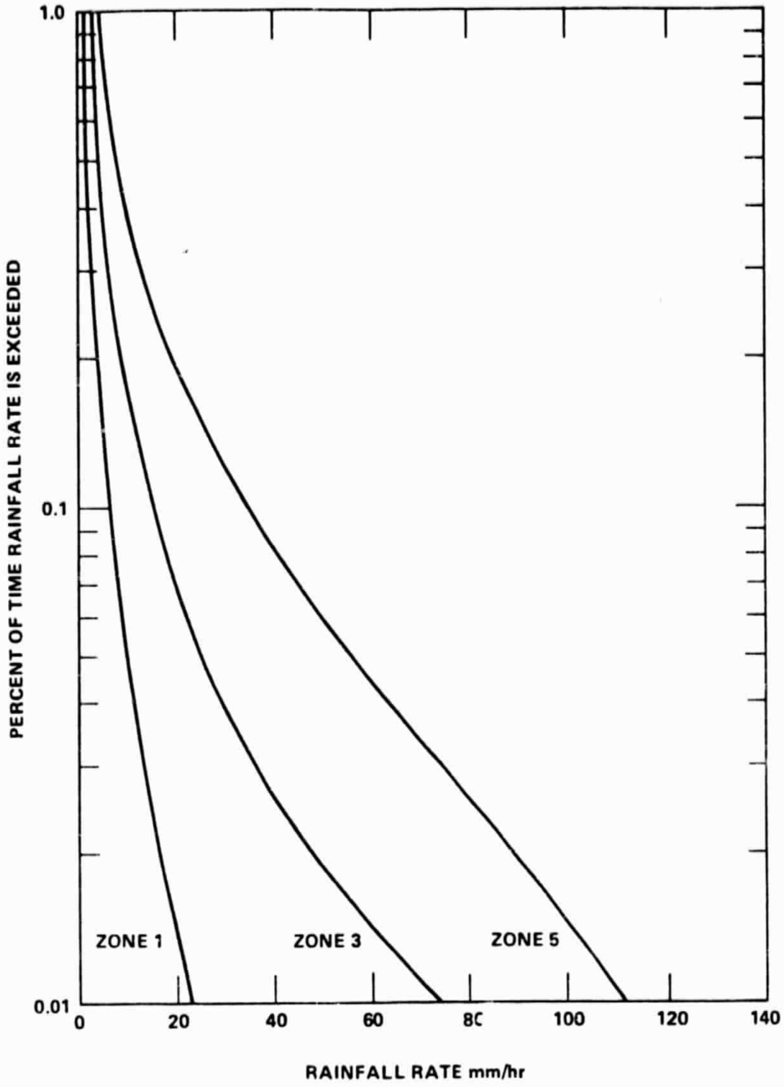


Figure 2.3-3. Cumulative Time Distribution of Rainfall Rate for Zones 1, 3, and 5

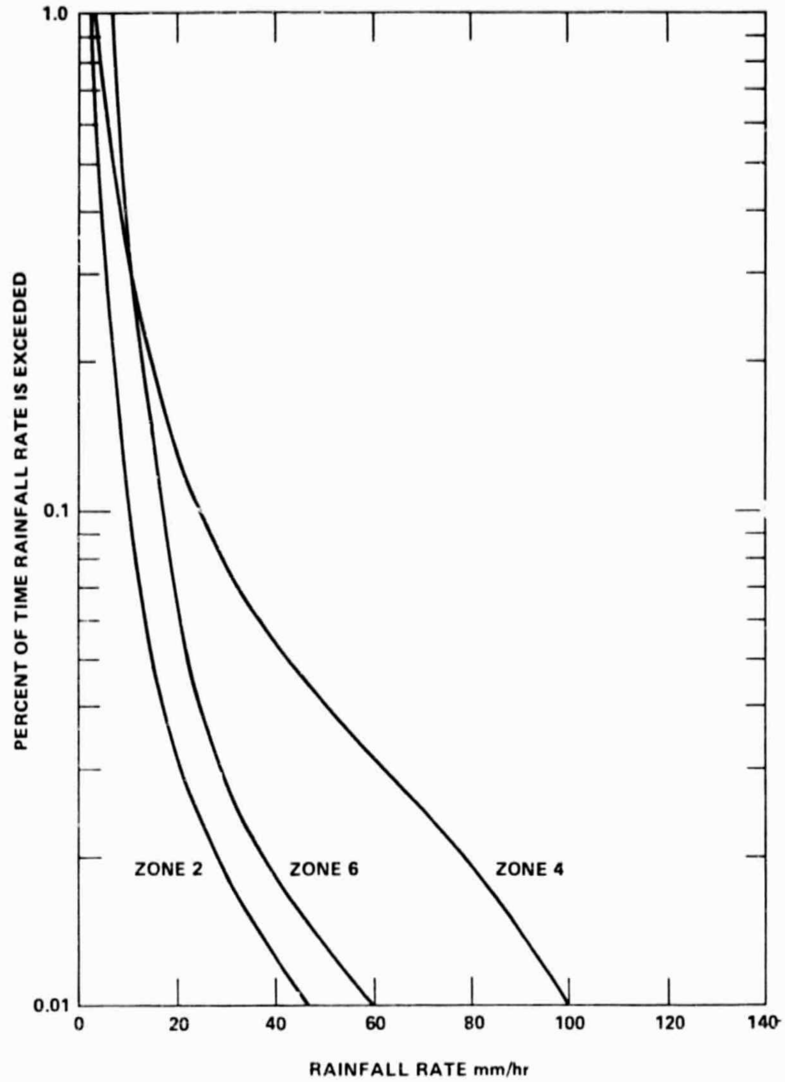


Figure 2.3-4. Cumulative Time Distribution of Rainfall Rate for Zones 2, 4, and 6

2.3.3 Propagation Attenuation for Rain Zones

Considerable uncertainty still exists in the prediction of the attenuation statistics, mainly in the area of effective path length definition. For the data presented in this section, we have used the CCIR model since it is the most recent and the most complete, taking into account more factors than the other models we examined. However, we believe that the CCIR model may lead to unrealistically large attenuation values at high rain rates, and there are indications that it may be slightly optimistic at very low rain rates. For low rain rates, therefore, the systems designer would be advised to provide a few decibels more margin than the attenuation values shown. Systems operating at very high rain rates will require diversity operation, and the exact knowledge of the single path attenuation is therefore not important. The attenuation values calculated with the CCIR model are shown in Table 2.3-1. These correspond to a 35° elevation angle to the satellite.

Table 2.3-1. Precipitation Margins Without Diversity

Frequency (GHz)	Single Link Availability (Percent)	Rain Zone					
		1	2	3	4	5	6
18*	99.0	1	2	2	3	3	4
	99.5	2	3	4	5	7	5
	99.9	4	7	8	13	19	10
	99.95	6	9	13	20	26	12
	99.99	13	23	35	49	54	28
30**	99.0	2	6	6	8	8	12
	99.5	5	8	11	14	17	16
	99.9	13	17	24	38	50	26
	99.95	18	25	35	65	75	34
	99.99	36	66	86	111	121	75

*A minimum margin of 3 dB is recommended for 18 GHz links.
**A minimum margin of 7 dB is recommended for 30 GHz links.

To account for the possible optimism of the CCIR method at low rain rates, FSI recommends a minimum propagation margin of 3 dB for single path 18 GHz links and a minimum margin of 7 dB for single path links of 30 GHz.

2.3.4 Space Diversity

Experiments in some areas of the United States have shown that heavy rain is highly localized with rain cells of only a few kilometers. A substantial amount of work has been done, and a model was developed by Hodge to permit the calculation of diversity gain as a function of site separation and single path attenuation. This relationship is illustrated in Figure 2.3-5. [Ref: Hodge, D.B. "A 15.3 GHz Satellite-to-Ground Diversity Experiment," Ohio State Electroscience Laboratory Report 2374-11, October 1972.]

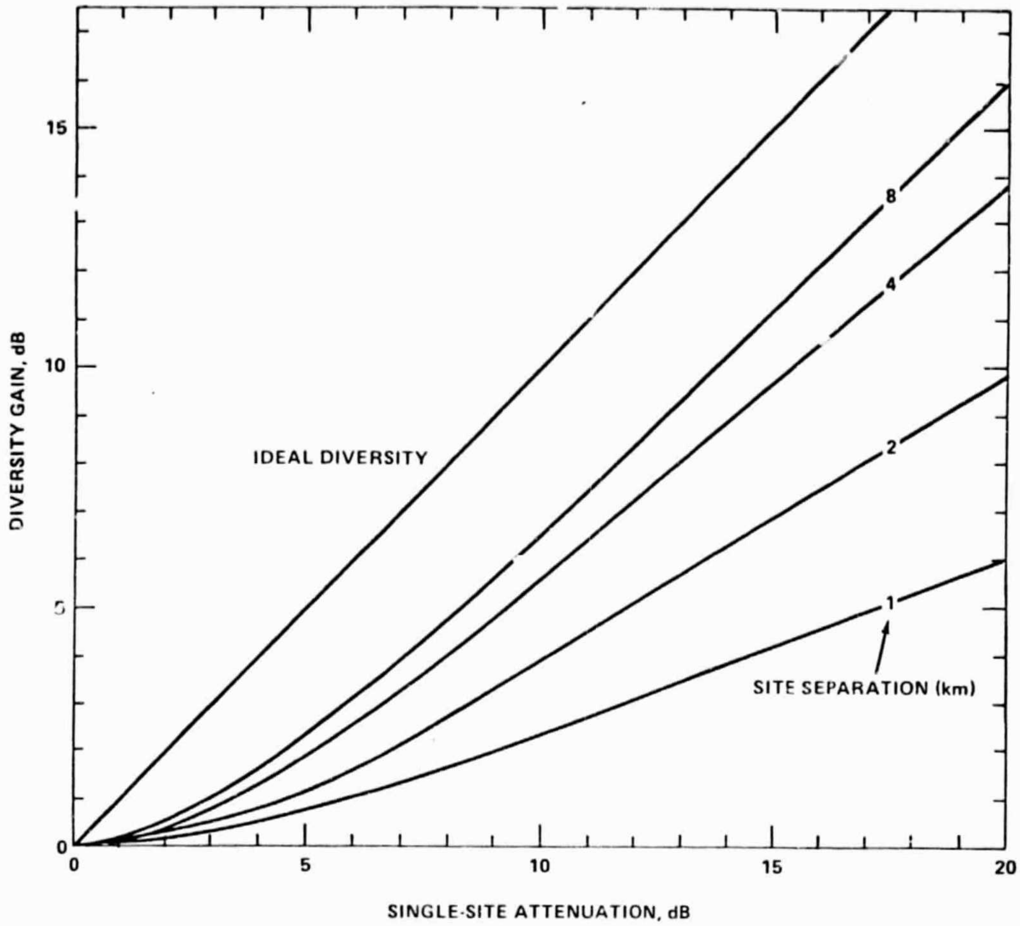


Figure 2.3-5. Diversity Gain for Various Separations

This diversity model shows that a site separation of 8 km reduces the required margins to approximately 4 to 5 dB maximum for realistic values of single-site attenuation. The 8 km spacing is already in the region of diminishing returns; an increase to 16 km gains only an additional 0.4 dB of diversity gain. A site separation of 2 km already provides substantial improvements. Margin requirements based on this model are shown in Table 2.3-2.

It should be noted that diversity gain measurements have been performed at only a few locations, and it is possible that other results would be obtained at other locations. Some doubts have been raised concerning the suitability of diversity operation for the case of widespread rain. Until additional data becomes available, it is recommended that several decibels of additional link margin be provided in addition to the margins based on the presently available diversity model as shown in Table 2.3-2.

Table 2.3-2. Precipitation Margins with Diversity (dB)

Frequency (GHz)	Single Link Availability (Percent)	Rain Zone					
		1	2	3	4	5	6
18	99.0	1	1	1	2	2	
	99.5	1	2	2	3	3	3
	99.9	2	3	3	4	4	4
	99.95	3	3	4	4	4	4
	99.99	4	4	4	5	5	4
30	99.0	1	3	3	3	3	4
	99.5	3	3	4	4	4	4
	99.9	4	4	4	5	5	4
	99.95	4	4	4	5	5	4
	99.99	4	5	6	6	7	5

Note: Due to uncertainties in the diversity model, it is recommended that diversity margins be increased by 2 dB at 18 GHz and by 4 dB at 30 GHz.

2.3.5 Earth Station Distribution Among Rain Zones

As a first approximation it is assumed that the earth station distribution will be identical to the population distribution among the six rain zones This distribution is as follows:

Rain Zone	Percent of Population
1	9.5
2	21.5
3	47.5
4	16.0
5	3.5
6	2.0

2.3.6 Rainfall and Outage Patterns

Communications systems are generally being designed to meet certain statistical availability requirements, for example, an availability of 99.9%, which would lead to cumulative communications outages of 525 minutes per year. While the total outage time is important, it is also of interest to generate a model of the distribution of outages and of the durations of individual outages. For this purpose we have generated a simple storm model based on weather statistics and performed a random simulation of rain occurrences for one winter and one summer month for a city in Rain Zone 3. The numbers of 18 GHz outages and outage durations were then listed for a range of transmission margins. The results are shown in Table 2.3-4.

Table 2.3-4. Storm Simulation Results for Chicago

18 GHz Margin (dB)	Month	Number of Outages	Total Minutes Outage	Percent of Month Availability
2.5	January	2	70	99.8
	July	18	595	98.7
5	January	1	30	99.93
	July	10	275	99.4
10	January	0	0	100.0
	July	3	65	99.8

2.3.7 Conclusions on Rain Attenuation

2.3.7.1 Required Availability

High availability of communications links is an important requirement today and will become even more important in the future. Some transmissions such as certain classes of facsimile, electronic mail, and batch processing data communications can be buffered and would not greatly suffer from rain outages. It is estimated, however, that these transmission types will be less than 10% to 20% of the total transmission volume throughout the rest of this century. The remaining 80% to 90% of the transmission volume will continue to be personto-person communications, for which any outages are considered to be inconvenient and undesirable.

Communications users will accept communications outages when no alternative communications media is available. This was the case in the 1950s and early 1960s when high frequency communications was the only transmission medium for certain intercontinental links. For U.S. domestic communications, however, the alternative to satellite communications is a well developed, high quality, reliable, and inexpensive terestrial communications system, which can and will be expanded and further improved during the next decades. Further transmission cost reductions that can be achieved with satellite communications will be of interest only if such links are of the highest quality and reliability. It must also be kept in mind that satellite links for real-time communications are basically inferior to terrestrial links because of the inherent satellite transmission delay.

The communications user is interested in overall end-to-end availability. Propagation outages are only one source of possible disruptions; other outages are possible due to equipment failure. Therefore, and for the reasons stated above, FSI believes that the following single earth station propagation availabilities will be desirable:

High volume trunking earth stations	99.99%
Direct-to-user earth stations	99.9%

However, a reduction in costs could well induce users to accept a lower availability for certain types of service. For such services the following availabilities would be appropriate:

At trunking earth stations	99.9%
At direct-to-user stations	99.5%

2.3.7.2 Required Uplink and Downlink Margins

Tables 2.3-5 and 2.3-6 show the uplink margins for each of the six rain zones that will be needed to meet the availabilities postulated in 2.3.7.1 for trunking and for DTU earth stations.

Table 2.3-5. Required Uplink and Downlink Margins (in Decibels) for High Availability Services

Station		Rain Zones					
		1	2	3	4	5	6
Trunking							
No diversity	downlink	13	23	35	49	54	28
	uplink	36	66	86	111	121	75
With diversity	downlink	6	6	6	7	7	6
	uplink	8	9	10	10	11	9
Direct-to-User							
No diversity	downlink	4	7	8	13	19	10
	uplink	13	17	24	38	50	26
With diversity	downlink	4	5	5	6	6	6
	uplink	8	8	8	9	9	8

Notes: 1. Propagation margins above 10 dB are undesirable and those above 20 dB are probably impractical.
2. Trunking at 99.99% availability.
3. Direct-to-user at 99.9% availability.

2.3.7.3 Diversity Operation

Paragraph 2.3.7.2 indicates that diversity operation will be important for the majority of transmission applications in 18/30 GHz systems. For this reason, the established diversity operation concepts should be further developed. Interconnection of diversity stations will be expensive, and therfore the concept of frequency diversity should be investigated in addition to space diversity.

2.3.7.4 Multifrequency Satellites

Because of the high propagation margins required without diversity and because of the complexity and cost of diversity operation, communications carriers and users will prefer the lower frequency bands. The 18/30 GHz band will be used only where and when the lower bands have become congested. At that time the 18/30 GHz band will be used as a supplement to communications via the lower frequency bands. Extensive connectivity will be required between earth stations and networks operating at each of the three satellite transmission bands: 4/6, 11/14, and 18/30 GHz. Since the delay of multihop operation is not acceptable for voice and for interactive data communications, this connectivity must be provided within

Table 2.3-6. Required Uplink and Downlink Margins (in Decibels) for Reduced Availability Services

Station		Rain Zones 1	2	3	4	5	6
Trunking							
No diversity	downlink	4	7	8	13	19	10
	uplink	13	17	24	38	50	26
With diversity	downlink	4	5	5	6	6	6
	uplink	8	8	8	9	9	8
Direct-to-User							
No diversity	downlink	3	3	4	5	7	5
	uplink	7	8	11	14	17	16
With diversity	downlink	3	4	4	5	5	5
	uplink	7	7	8	8	8	8

Notes: 1. Propagation margins above 10 dB are undesirable and those above 20 dB are probably impractical.
2. Trunking at 99.9% availability.
3. Ditect-to-user at 99.5% availability.

satellites and by intersatellite links. For this reason, commercial satellite communciations systems using the 18/30 GHz band will also employ the lower frequency bands in the same satellites, and switching facilities will be needed on board to provide flexible connectivity between beams and frequency bands.

2.3.8 Recommendations for Further Work on Rain Attenuation

The scope of effort for the propagation study of this report is limited. Several areas in which further work would be desirable in order to identify the parameters of an operating system are desribed.

2.3.8.1 Effective Path Length

Knowledge of the effective path length or path length of equivalent uniform rain rate is required to predict total attenuation as a result of measured surface rain rate. At present, there are substantial variations among various models. The CCIR model, for example, is suspected of being optimistic at low rain rates and pessimistic at high rain rates.

The generation of an improved model of effective path length would be desirable in order to permit prediction of single path precipitation attenuation with greater confidence. This would require the evaluation of additional data on propagation experiments that are being conducted by Comsat Labs, Bell Labs, and by others, and perhaps additional measurements could be performed for NASA with the use of the Comstar beacons.

2.3.8.2 Diversity Path Attenuation

The best present model for diversity gain is that derived by Hodge. Coupled with the CCIR single path attenuation model, it leads to very low propagation margin requirements with diversity operation. Some reviewers believe that this model may be optimistic under certain climatic conditions, and, specifically, that it may not fully allow for the effects of widespread rain. Since diversity operation is very important at 18/30 GHz, it is desirable to improve the confidence in a diversity attenuation model.

The most direct method of acquiring additional data would be taking long-term attenuation measurements at diversity sites at a range of locations representing different climatic zones. Such measurements would simultaneously satisfy the requirements for effective path length determination as defined above. Additional measurements with the use of the Comstar beacons would be well suited for this task. In addition to propagation measurements, diversity rain rate measurements would be desirable. Varying diversity site distances as well as varying climatic zones should be considered in these experiments, which should extend over at least 1 year in order to obtain sufficient statistical data.

2.3.8.3 Rainstorm Models

In designing a transmission link, total cumulative outage time as well as information on outage times and distributions of outages versus time is important. Better storm models are needed in order to determine outage times and distributions of outages versus time of the day, month, and year. Information on instantaneous rain rates, attenuations, and variation of rain rates and attenuation with time is required. The experiments described under 2.3.8.1 and 2.3.8.2 above can provide this information if they are appropriately structured. As a result, it would be possible to simulate attenuation events as a function of time for a range of climatic locations and to identify outage times and distributions for different propagation margins with and without diversity. Such models would be valuable in the communications systems design.

2.3.8.4 Frequency Diversity Operation

Frequency diversity operation promises to be less costly than space diversity operation since it avoids the need for interconnection of diversity stations. An earth station using frequency diversity would have to be equipped to operate at two frequencies, and the lower frequency would be used only during periods of heavy rain. Common baseband equipment would be used.

In this concept, some portion of a lower frequency band would have to be reserved for diversity switching in each antenna beam. The percentage of reserved bandwidth would depend on the storm statistics, and it can be determined from the experiments described under 2.3.8.1 and 2.3.8.2 above. The use of the 4/6 GHz band would be preferable from an attenuation point of view, but frequency coordination may be a problem at many locations. For these cases, the 11/14 GHz band should be used for diversity switching, although it would require higher transmission margins than the 4/6 GHz band.

Frequency diversity operation requires switching on board the satellite and on the ground. Associated switching and sensing requirements should be determined.

SECTION 3

MAJOR TERMINAL TRUNKING CONCEPTS

The trunking type of satellite communications system at 18/30 GHz is designed to accommodate a relatively small number of earth terminals (10 to 40) which may be located anywhere within the continental United States (CONUS) excluding Alaska. The main feature of this type of configuration is that the user terrestrial network distribution ("tails circuit") costs are higher than that of direct-to-user (DTU) systems because of the relatively few terminal locations. For trunking systems the total cost of the spacecraft segment generally exceeds that of the terminal segment and hence it becomes important to optimize the performance/cost relationship for the spacecraft design.

The approach used to document trunking concepts is (1) define overall requirements and coverage tradeoffs, (2) define a detailed baseline system configuration using FDMA, (3) define a summary approach using TDMA, and (4) examine other tradeoff alternatives. System costs and performance will be used as measures of relative desirability.

It is not to be interpreted that the baseline configuration is an optimized design. Rather it is a viable total system concept that may be used to encompass all related system parameters in a unified framework that serves as a reference for evaluating the relative desirability of alternatives.

A large number of technical, economic, political, and user demand factors will influence future trunking system configurations at 18/30 GHz. These factors include the communications demand growth as a function of quality and circuit availability, scenarios for determining which companies will control or share control of the satellite network, desirability of large multifrequency-band satellites versus smaller single-band satellites, desirability of uniform performance within CONUS independent of nonuniform demand, etc. Until the associated requirements for the satellite communications link are fully modeled, it is impossible to determine optimum configurations.

Subsection 3.1

Trunking Requirements/Overview

The communication requirements for trunking satcom operation are not firm at this time. To a certain degree the services demand requirements may be determined by the performance and cost of viable system concepts.

A baseline set of requirements was selected to provide a starting point for the configuration concept analysis. Subsequent analysis shows the impact of variances to the baseline. The range of configurations and performance parameters for trunking operation is shown in Figure 3.1-1. The delineated path within the matrix shows the baseline concept configuration. Selection criteria were established as follows:

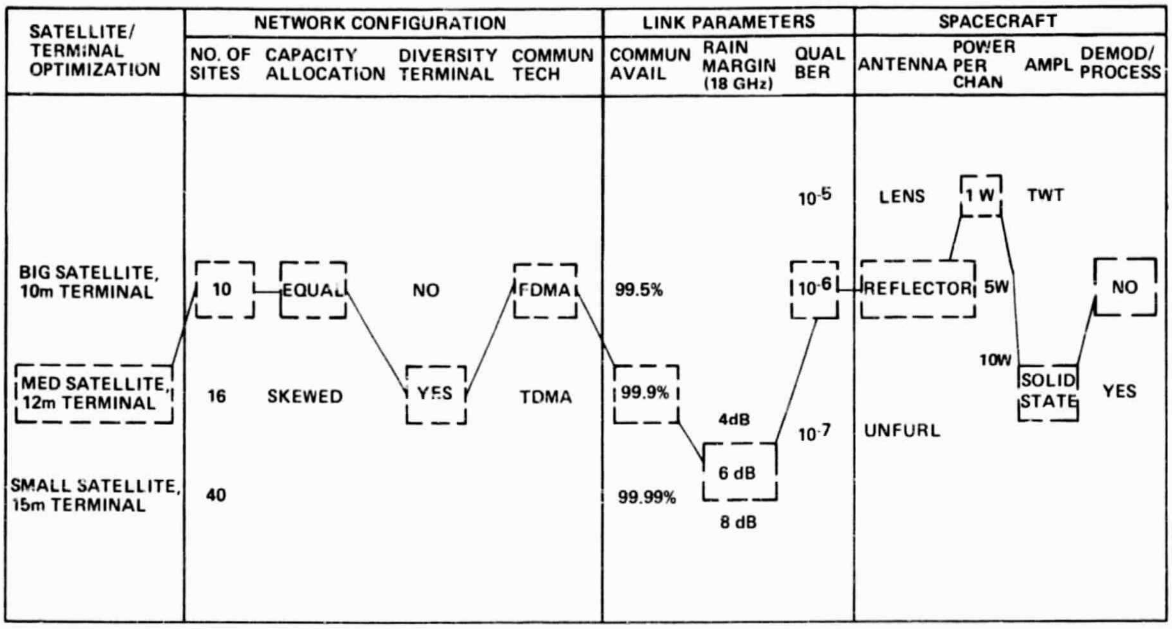


Figure 3.1-1. Trunking System Configuration Options

Satellite/Terminal Optimization

It is possible to operate trunking systems with a large spacecraft and 10 m diameter terminals, a medium spacecraft and 12 m diameter terminals, or a small spacecraft with 15 m diameter terminals. A medium spacecraft and medium terminal were selected for the baseline because the feasibility of the 12 m diameter terminal design has already been established. A larger spacecraft is examined subsequently as an alternative.

A small spacecraft does not present a viable alternative because the spacecraft cost savings is small and significant technical problems are associated with earth terminals larger than 15 m diameter. Other criteria that affect the selection are determined by the STS launch vehicle

characteristics. In general, the share of launch costs is determined by spacecraft and associated perigee motor length rather than weight. Because the overall length is relatively constant for a wide range of spacecraft power levels, the launch vehicle cost benefits associated with small spacecraft are minimal.

Network Configuration

The system capacity should be matched to user demand. The unit spacecraft throughput data rate can be established over a broad range up to 50 Gb/s or more. A capacity of about 25 Gb/s was selected for the baseline, which evolved from a full interface of 10 trunking sites at 274 Mb/s among all sites.

A baseline design for the first generation system is based on 10 trunking terminal sites to minimize interconnect requirements and yet accommodate a large part of total capacity needs. The spacecraft antenna technology for multiple spot beams permits up to about 50 beams; however, the physical constraints on feed layout and interbeam isolation requirements will limit the number of spot beams in the highly concentrated demand areas.

For the baseline it is assumed that all of the spot beams are equal in size (about 0.3° half power beamwidth) and that equivalent performance EIRP and G/T are presented to any point within CONUS. An equal data capacity per beam is assumed. It is recognized that any optimized system configuration should match the real user distribution as much as possible. The other variable is the percent of traffic from given trunking terminal areas that may be carried by alternate methods such as other satcom transmission frequencies (C-band and K_U-band), or terrestrial networks.

The selection of communications technique impacts upon the flexibility for network implementation. A frequency division multiple access (FDMA) system is assumed for the baseline; however, a time division multiple access (TDMA) system is also examined as a viable alternative.

Link Parameters

Significant attenuation of signal transmission is incurred at the 18/30 GHz bands during heavy rainfall. Link margins may increase in order to minimize the outage during heavy rain; however. the system costs rise rapidly. The baseline trunking design provides 99.9% communications availability (ie, 9 hours of outage per year) to diversity earth terminals through use of 6 dB rain margins at 18 GHz and at 30 GHz. A communications bit error rate (BER) of 10^{-6} is assumed. Computer-to-computer data transfer at 10^{-7} to 10^{-9} BER may be achieved by trading off bandwidth capacity for error correcting coding.

It would be very desirable to improve the communications availability to 99.99% (ie, 0.9 hours of outage per year); however, the link margins would have to be increased significantly to meet this performance level.

Spacecraft Configuration

CONUS spot beam coverage may be obtained with a dual reflector spacecraft antenna at 18 GHz and a separate antenna for 30 GHz. A lens type antenna and large unfurlable antennas provide other design alternatives.

It is possible to provide 25 Gb/s throughput capacity with single use of a 2.5 GHz bandwidth available at K_A band by using QPSK modulation. Because a dual antenna approach per frequency was selected to minimize feed location problems, it also becomes feasible to use polarization diversity coupled with frequency diversity. This simplifies the filtering requirements.

The baseline spacecraft has a transponder configuration that filters uplinks and provides a hardwired interconnect of the 90 destination rf signals. A separate solid state power amplifier of 1 W output per channel is incorporated in the baseline design.

No signal processing with associated buffer storage and special routing is required for the baseline design. These techniques do offer improvements in overall communications efficiency; however, long-term spacecraft reliability is compromised and higher data rates are not expected to be needed for the first generation system implementation.

Subsection 3.2

Baseline FDM Trunking System

This section defines a baseline satcom configuration using frequency division multiple access (FDMA) to meet the postulated trunking requirements. The dashed path of previous Figure 3.1-1 shows the parametric decisions for this approach. A general concept of the baseline design is summarized in Figure 3.2-1.

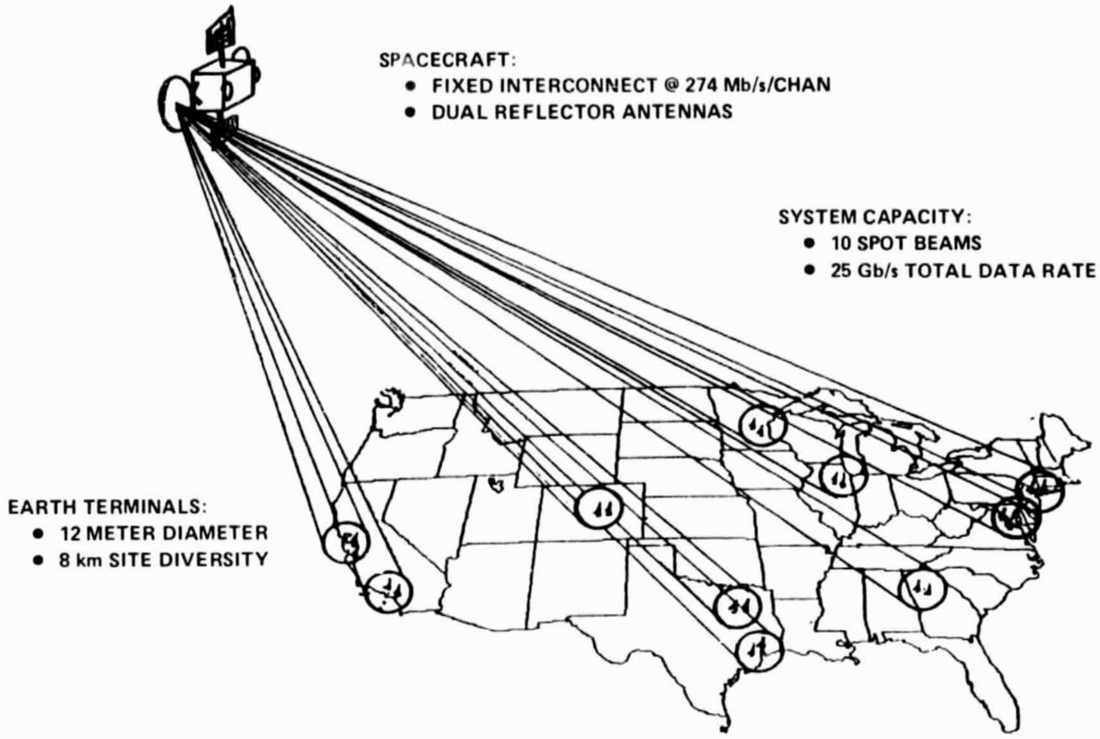


Figure 3.2-1. Trunking Network Configuration

3.2.1 System Configuration

This system configuration is designed for high data rate trunking application among 10 terminals within CONUS. A nominal 165 MHz bandwidth capacity is provided among all of the terminal pair combinations via FDMA with hardwired interconnect in the spacecraft. The bandwidth required for nine interconnect channels is about 1.5 GHz. This yields a spare capacity for systems growth of 1.0 GHz as shown in the frequency plan of Figure 3.2-2. QPSK modulation is utilized to provide 99.9% propagation reliability at a bit error rate of 10^{-6}. Communications capacity is 2.5 Gb/s per site, which results in a full system capacity of 25 Gb/s.

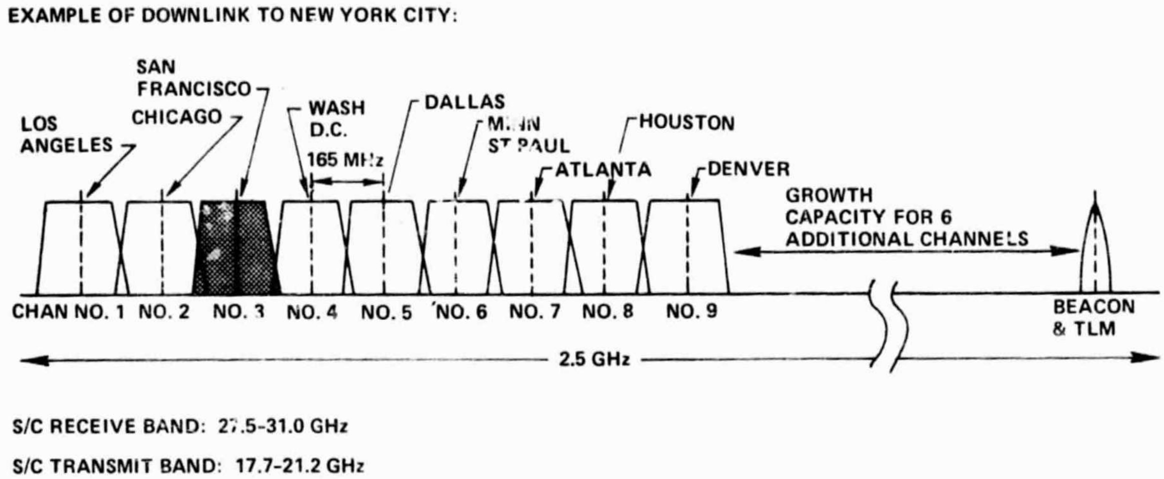


Figure 3.2-2. Frequency Plan for 10-Site Trunking System

The spacecraft is Shuttle launched and placed into transfer orbit with an SPM-4 or upgraded SSUS-A perigee motor. The spacecraft has a payload weight of 2420 lb on orbit and provides about 1.1 kW of solar power at beginning of life. The rf power per channel per beam is 1.0 W, and FET amplifiers are used. The satellite design lifetime is 10 years. A four-satellite program is planned, namely a qualification model that is later refurbished to flight level, two satellites for initial launch into synchronous orbit, and one additional spare satellite.

The earth terminals are 12 meters in diameter and a diversity terminal at a minimum separation of 8 km is provided at each site. Inputs to the earth terminals from the switching centers are provided at standardized PCM data rates (nominally 274 Mb/s) on separate lines associated with each destination terminal. The transmitter power per channel is 20 W in the normal mode and increases in steps up to 60 W during rainstorm periods. The key factors in determining the baseline trunking design parameters are listed in Table 3.2-1.

The network provides equivalent 200 MHz bandwidth interconnect among the minimum number of terminals specified in the statement of work. An equal allocation of data rate among cities is assumed in the absence of a detailed data requirements model. QPSK modulation yields spectrum usage efficiency with no associated power penalty. The size of the

Table 3.2-1. Key Factors in Determining Trunking System Baseline Design

Network

- Ten terminal sites per statement of work
- Interterminal data rate of 274 Mb/s per standarization of T-4 carrier
- Equal allocation of data rate among cities
- QPSK modulation for spectrum efficiency with no power penalty

Launch vehicle

- Maintain compatibility with Shuttle and SSUS-AA

Satellite

- Antenna diameter to 15 ft per shuttle constraints
- Rf power per channel of ∿1 W to permit use of solid-state FET amplifiers

Terminals

- Limit of 12 m diameter to permit rooftop installations
- Use of geographic diversity for high communications reliability and uplink power balance

spacecraft and its antenna structure is limited to the 15 ft diameter of the Shuttle launch vehicle and hence elaborate erecting mechanisms are not required. The rf power per channel is sized to about 1 W in order to permit use of solid state amplifiers that may lead to improved long-term reliability. The earth terminals are limited to 12 m diameter to facilitate spacecraft tracking during high wind conditions from rooftop installations. Geographic diversity provided by a pair of earth terminals per site permits high communication availability and helps maintain uplink power balance.

Details on general system specifications for the baseline FDMA trunking configuration are given in Table 3.2-2.

Table 3.2-2. Baseline FDMA Trunking System Parameters

System	
Wideband trunking system among 10 terminals	
FDMA modulation with hardwired satellite interconnect	
Equal allocation of 285 MHz bandwidth (duplex) among all stations	
Ten spacecraft spot beams of ≈ 0.3° half-power beamwidth (18 GHz)	
Satellite positioned at 100° W longitude	
Communications	
QPSK modulation at 10^{-6} BER	
274 Mb/s data rate (T-4 carrier) within 165 MHz channel bandwidth	
System link margin of +3 dB minimum	
99.9% propagation reliability	
Use of 5 dB downlink rain margin to accommodate light rain	
Use of 8 km terminal site diversity to accommodate thunderstorms	
Satellite	
Launch vehicle:	Shuttle launch in 1985-1990 time period
Perigee motor:	SSUS-A
No. of satellites:	Refurbished qualification +3 flight models
Antenna:	One dual reflector downlink antenna of 14 ft diameter
	One dual reflector uplink antenna of 12 ft diameter
	Beam isolation of 25 dB minimum including polarization diversity
Antenna pointing:	To within ± 0.1° including alignment
Communications:	Single FET power amplifier per channel (90) plus spares
	RF power of 1 W per channel per beam
TT&C:	Use K_A band for beacon and TT&C link
Eclipse operation:	Battery capacity for 100% operation thru max eclipse
Spacecraft weight:	4600 lb including apogee motor
Spacecraft power:	1400 W solar at BOL
Earth Terminals:	
Network:	Ten-site location within CONUS
Diversity:	Dual terminals separated by minimum of 8 km
Antenna diameter:	12 m
Transmitter power:	Variable over range of 20 W to 100 W per channel
Receiver noise:	Cooled paramp receiver with 120 K noise temperature
Modems:	Demodulate to trunking rate per channel (nominally 274 Mb/s)

If the traffic distribution model for 18/30 GHz satcom trunking communications were similar to the current intercity demands then the 10 city traffic model would be similar to that of Table 3.2-3. The imbalance of traffic among cities, for example, shows that New York City has the greatest demand (22% of the total 10 city model) whereas Denver has the least demand (4% of the total 10 city model). A preliminary 10 city interconnect model is shown in Table 3.2-4. Communications techniques are available to accommodate a skewed traffic demand and are discussed as alternatives to the baseline configurations.

Table 3.2-3. Ten-City Traffic Distribution Model

CITY	% OF TOTAL INTERCITY TRAFFIC	% OF TRAFFIC TO NEW YORK CITY
NEW YORK	22.4%	
CHICAGO	17.4	5.4%
LOS ANGELES	17.3	5.4
SAN FRANCISCO	8.4	2.3
WASHINGTON, D.C.	8.0	2.2
DALLAS	6.3	1.7
HOUSTON	6.3	1.7
MINN/ST PAUL	5.3	1.4
ATLANTA	4.8	1.3
DENVER	3.8	1.0
	100.0%	22.4%

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The spacecraft antenna interbeam interference level limits the minimum separation distance of site locations if frequency diversity cannot be employed because of full use of spectrum by both sites. The half power beamwidth (-3 dB) and the beam patterns, which are -25 dB down from peak of beam, are shown in Figure 3.2-3. It is possible that a New York City site and a Washington, D.C. site would have sufficient geographic separation to be resolved by spot beams; however, it would be impossible to also have a simultaneous beam coverage of Philadelphia and Baltimore areas. A two-satellite configuration on-orbit would permit better coverage of the closely spaced city regions of northeastern CONUS.

Table 3.2-4. Ten-City Communications Interconnect Model

Originating	Terminating									
	New York	Chicago	Los Angeles	San Francisco	Washington, D.C.	Dallas	Houston	Minn./St. Paul	Atlanta	Denver
New York (22.4%)		24.1	23.9	10.3	9.9	7.6	7.6	6.3	5.7	4.4
Chicago (17.4%)	31.0		21.7	9.4	9.0	7.0	7.0	5.7	5.2	4.0
Los Angeles (17.3%)	30.9	21.8		9.4	9.0	6.9	6.9	5.8	5.2	4.0
San Francisco (8.4%)	27.6	19.4	19.3		8.0	6.2	6.2	5.1	4.5	3.6
Washington, D.C. (8.1%)	27.5	19.9	19.3	8.3		6.2	6.2	5.0	4.5	3.5
Dallas (6.3%)	27.0	19.1	18.9	8.2	7.9		6.0	5.0	4.4	3.5
Houston (6.3%)	27.0	19.1	18.9	8.2	7.9	6.0		5.0	4.4	3.5
Minn./St. Paul (5.3%)	26.7	18.8	18.9	8.1	7.5	6.0	6.0		4.5	3.4
Atlanta (4.8%)	26.6	18.9	18.9	8.0	7.5	5.9	5.9	5.0		3.6
Denver (3.8%)	26.4	18.7	18.4	8.0	7.5	5.9	5.9	4.8	4.5	

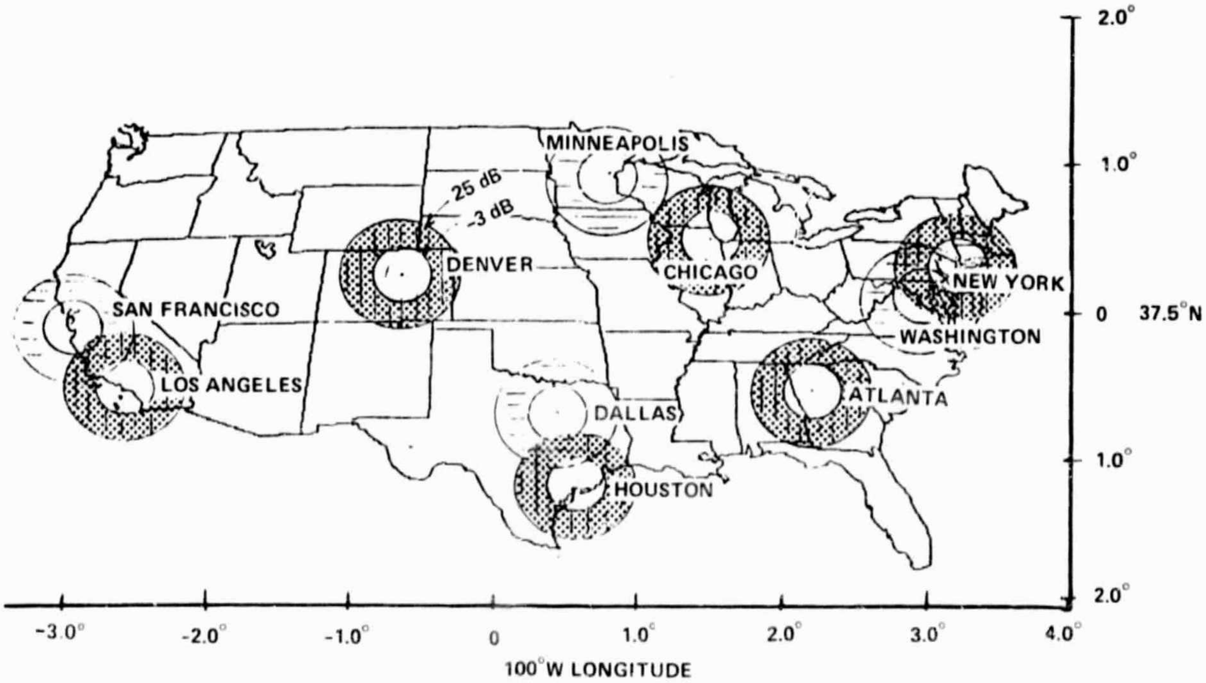


Figure 3.2-3. Antenna Coverage for 10-Site Trunking System

3.2.2 Trunking Communications Links

This paragraph describes the baseline design configuration of the trunking communications link. The link budget allocation and predicted performance characteristics for single and diversity earth terminal configurations are described.

A layout of the baseline FDMA trunking link configuration is shown in Figure 3.2-4. Information originating at a Los Angeles trunking site for routing to nine destination cities is grouped in nine separate 274 Mb/s data channels. The information destined for New York City, for example, is multiplexed, amplified, and transmitted on a separate carrier within the overall transmit bandwidth of 27.5 GHz to 31.0 GHz. During clear weather a 20 W transmitter is utilized per channel; however, during heavy rain periods a 60 W amplifier may be used. To minimize the impact of rain attenuation, a diversity selection is made between two geographically separated terminals at each site. The terminal separation of 8 km or more assures that thunderstorm type rain of high intensity but small coverage area rarely impacts both terminals simultaneously.

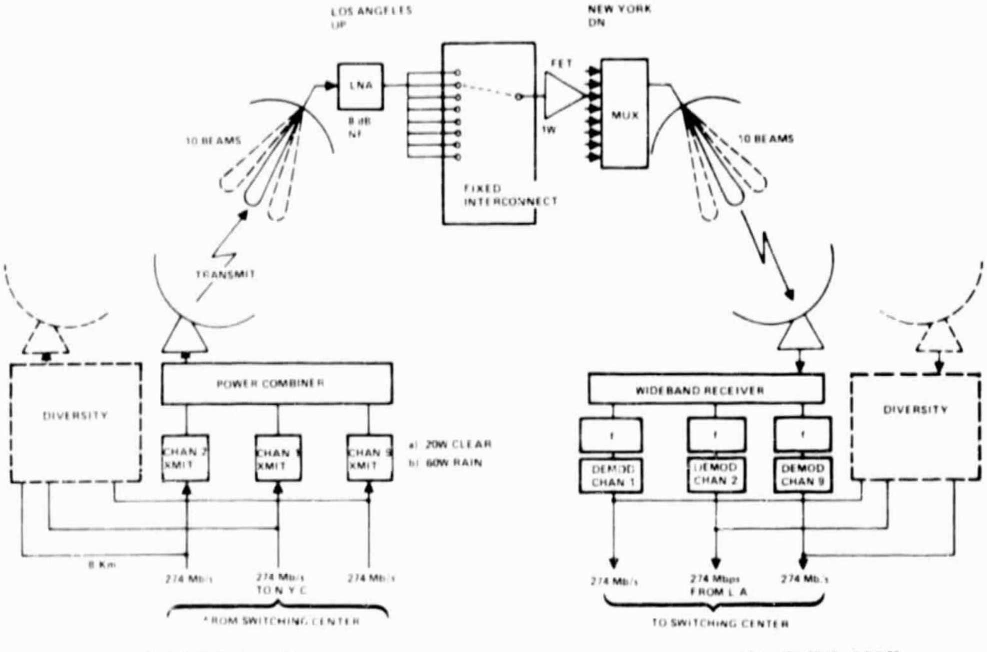


Figure 3.2-4. Baseline Link Configuration

The spacecraft receives the Los Angeles originated signals in one of the 10 spot coverage beams. A low noise amplifier with noise figure of 8 dB or less is used as the receiver. The signals are filtered into nine separate destination channels and connected to the appropriate downlink beam by means of fixed interconnect within the spacecraft. Each of the 90 separate data channels is amplified with a 1 watt rf solid state amplifier and multiplexer combined in

beam from the combination of all other beams cannot exceed the capacity of the 2.5 GHz of spectrum bandwidth allocation. The baseline design for full interconnect of equal 274 Mb/s (T-4 carrier) data link among 10 sites yields a total spacecraft throughput data capacity of 25 GB/s. QPSK modulation is used for spectrum bandwidth efficiency with no power loss.

The receiving terminal receives nine separate rf carriers within the 17.7 GHz to 21.2 GHz downlink transmission band, then filters, amplifies, and demodulates to recover the 274 Mb/s data rates. A diversity terminal at 8 km separation assures low communications outage of less than 0.1%.

3.2.2.1 Trunking Link Budget

A summary link budget for the baseline trunking satcom communications link is given in Table 3.2-5, and additional details are provided in Tables 3.2-6 through 3.2-8. One of the key factors affecting link design is the amount of margin to accommodate rain attenuation. It is expected that a 10^{-6} bit error rate quality could be maintained for 99.9% of the time if space diversity terminals (8 km separation) were used at each trunking site and if an uplink rain margin of 5 dB and a downlink margin of 4 dB are provided. Additional details on the effects of rain are provided in paragraph 3.2.2.2.

Table 3.2-5. Summary Link Budget for 274 Mb/s QPSK

	Case 1 No Rain	Case 2 Uplink Rain	Case 3 Downlink Rain
Uplink (30 GHz)			
Ground Antenna gain (12 meter dia)	+ 69.0 dB		
Transmitter power per channel	+ 13.0 dBW	+ 17.8	
Rain attenuation for 99.9% reliability	0	− 5.0	
Satellite antenna gain (12 ft dia)	+ 57.7 dB		
Uplink net C/kT	+109.2 dB-Hz	+109.0 dB-Hz	+ 109.2 dB-Hz
Downlink (18 GHz)			
Satellite Antenna gain (14 ft dia) peak	+ 54.7 dB		
Pointing loss for ± 0.1°	− 1.3 dB		
Off axis scan (± 3°) degradation	− 0.5 dB		
Transmitter power/channel/beam (1.0 W)	− 0.0 dB		
Rain attenuation for 99.9% reliability	0		− 4.0
Ground antenna gain (12 meter dia)	+ 64.9 dB		
Noise temperature	− 22.8 dB · K		− 24.8
Downlink net C/kT	+109.9 dB-Hz	+109.9 dB-Hz	+103.9 dB-Hz
Combined link			
Total up and down C/kT	+106.5 dB-Hz	+106.5	+102.7
Required system C/kT	+ 98.2 dB-Hz	+ 98.2	+ 98.2
Net system margin (With 8 km ground diversity)	+ 8.3 dB	+ 8.3 dB	+ 4.5 dB

Table 3.2-6. Link Budget for 274 Mb/s QPSK

	Case 1 No Rain	Case 2 Uplink Rain	Case 3 Downlink Rain
Uplink (30 GHz)			
Ground antenna gain (12 m dia)	+69.0 dB		
Waveguide losses	- 1.6 dB		
Transmitter power per channel	+13.0 dBW	+17.8 dBW	
Power amplifier combining losses	-5.0 dB		
Pointing loss	-0.4 dB		
Propagation path loss (45° elevation)	-213.5 dB		
Atmospheric attenuation – clear sky	-1.1 dB		
Rain attenuation for 99.9% reliability	0	-5.0	
Boltzmann constant	+228.6 dBW/kHz		
Satellite antenna gain (12 ft dia)	+57.7 dB		
Feed and line losses	-1.5 dB		
Pointing loss for ±0.1°	-3.6 dB		
Off-axis scan (±3°) degradation	-0.5 dB		
Receive noise temperature (NF = 8 dB)	-31.9 dB		
Uplink net C/kT	+109.2 dB-Hz	+109.0 dB-Hz	+109.2 dB-Hz
Downlink (18 GHz)			
Satellite antenna gain (14 ft dia) peak	+54.7 dB		
Pointing loss for ±0.1°	-1.3 dB		
Off-axis scan (±3°) degradation	-0.5 dB		
Feed and line loss	-1.0 dB		
Transmitter power/channel/beam (1.0 W)	-0.0 dB		
Power combining loss	-2.5 dB		
Propagation path loss (45° elevation)	-209.1 dB		
Atmospheric attenuation	-0.5 dB		
Rain attenuation for 99.9% reliability	0		-4.0
Boltzmann constant	+228.6 dBW/kHz		
Ground antenna gain (12 m dia)	+64.9 dB		
Noise temperature	-22.8 dB-K		-24.8 dB-K
Waveguide loss	-0.3 dB		
Pointing loss	-0.3 dB		
Downlink net C/kT	+109.9 dB-Hz	+109.9 dB-Hz	+103.9 dB-Hz
Combined Link			
Total up and down C/kT	+106.5 dB-Hz	+106.5 dB-Hz	+102.7 dB-Hz
Required system C/kT	+98.2 dB-Hz	+98.2 dB-Hz	+98.2 dB-Hz
Net System Margin (with 8 km ground terminal diversity)	+8.3 dB	+8.3 dB	+4.5 dB

Table 3.2-7. Details of Link Calculation

Uplink Parameters

a. Ground Terminal

1. Ideal on-axis gain of 12 m dish of 71.5 dB less aperture efficiency loss with 0.02 inch rms surface of 2.5 dB equals net on-axis gain of +69.0 dB
2. Waveguide losses of 1.6 dB for power amplifiers located in shelter rather than on pedestal.
3. Power combiner loss associated with combining of nine separate power amplifiers into a single antenna feed is estimated to be -5 dB.
4. Individual channel power amplifiers are assumed to be of variable power mode. The clear sky power is 20 W per channel obtained by TWT operated at backoff. A maximum of 60 W per channel is used during heavy rain conditions.
5. Half-power beamwidth of the 12 m dish is 0.06° at 30 GHz. Antenna tracking is required and it is estimated that the maximum pointing loss is -0.4 dB during high wind conditions. This corresponds to an overall pointing accuracy of ±0.01°.
6. The net ground terminal EIRP at maximum pointing loss is therefore +75.0 dBW per channel for clear sky conditions.
7. The EIRP increases to +79.8 dBW during heavy rain periods.

b. Propagation Losses

1. The path loss associated with a 45° elevation angle to the spacecraft is -213.5 dB. If the spacecraft is located at 100°W longitude, then the elevation angles for the cities associated with a 10-terminal trunking system range from 32° (New York) to 55° (Houston). The extremes would change the path loss factor by ±0.2 dB.
2. The normal atmospheric attenuation during clear sky conditions is -1.1 dB for 10 grams of water per cubic meter.
3. An additional rain attenuation factor for a 99.9% condition at 30 GHz when using the best of two diversity terminals separated by at least 8 km is about -5 dB.

c. Satellite Receiving

1. The on-axis ideal gain of the 11.2 ft projected aperture obtained from a 12 ft diameter main reflector is +60.4 dB at 30 GHz. Losses for polarization efficiency, spillover efficiency, and aperture efficiency reduce the ideal gain by 2.7 dB.
2. Off-axis scan degradation associated with scan angles of ±3° off beam center is -0.5 dB.
3. The receiving antenna feed and line loss is -1.5 dB.
4. The half-power beamwidth of each antenna beam is 0.23°.
5. A spacecraft antenna pointing loss of -3.6 dB is obtained from a ±0.1 error in worst case condition.

d. Net Uplink C/kT. The net uplink C/kT in clear sky condition is +109.2 dB-Hz.

Downlink Parameters

a. Satellite

1. Satellite transmitting power of 1 W per channel is obtained by operating solid-state FET amplifier at saturation.
2. Loss in combining nine power amplifiers into a single beam is estimated to be -2.5 dB.
3. The on-axis gain of the 12.8 ft projected aperture obtained from a 14 ft diameter main reflector is +57.4 dB at 18 GHz. Losses for polarization efficiency, spillover efficiency, and aperture efficiency reduce ideal gain by -2.7 dB.
4. Off-axis scan degradation associated with scan angles of ±3° off beam center is -0.5 dB. The half-power beamwidth is 0.3° in one plane and 0.36° in the cross plane.
5. The line loss from output of power combiner to antenna feed is -1.0 dB.
6. A spacecraft antenna pointing loss of -1.3 dB is obtained from an overall alignment and attitude control error of ±0.1°.

b. Propagation Losses

1. The path loss associated with a 45° elevation angle to the spacecraft is -209.1 dB. If the spacecraft is located at 100° W

Table 3.2-7. Details of Link Calculation (Continued)

longitude (baseline) then the elevation angles for the cities associated with a 10-terminal trunking system range from 32° to 55°. These extremes would change the path loss factor by ±0.2 dB.

2. A standard atmospheric attenuation factor of -0.5 dB is obtained during clear weather conditions.
3. An additional rain attenuation factor for a 99.9% condition at 18 GHz is about -4 dB when using the best of two diversity terminals separated by at least 8 km.

c. *Ground Terminal*

1. Ideal on-axis gain for 12 m reflector of 67.1 dB less feed and aperture efficiency loss (0.02 inch rms surface) of 2.2 equals a net on-axis gain of +64.9 dB.
2. Waveguide loss for LNA mounted on pedestal is estimated to be -0.3 dB.
3. The half-power beamwidth of the 12 m diameter dish is 0.10° at 18 GHz. Antenna tracking is required, and it is estimated that the maximum pointing loss is -0.3 dB during high wind conditions.
4. A thermoelectric cooled paramp receiver of 120 K noise temperature and clear sky noise temperature of 70 K would result in a receiving system noise of 190 K or -22.8 dB/K during clear weather. The sky noise would increase to about 180 K for 5 dB rain attenuation; hence, the system noise increases to 300 K or -24.8 dB during 99.9% rain conditions.

d. *Net Downlink C/kT*. The net downlink C/kT in clear sky condition is +109.9 dB.

Combined Link Parameters

a. In clear sky conditions at both uplink and downlink, a combined system C/kT of +106.5 dB is obtained. In this case the uplink is penalizing the downlink by -3.4 dB; however, adequate system margin is obtained. The uplink is designed to penalize the downlink by 1.2 dB during downlink rain operation.

b. Required system C/kT for 274 Mb/s at 10^{-6} BER when using QPSK is +98.2 dB-Hz. This factor includes a +3 dB margin for system and equipment degradation to theoretical values.

c. A net system margin of +8.3 dB is obtained for clear sky operation, +8.3 dB during uplink rain, and +4.5 dB for downlink rain. This margin is obtained for the 99.9% communications reliability.

Table 3.2-8. C/kT Requirements

E_b/N_o Theoretical for 10^{-6} BER	10.8 dB
Bit Rate Factor (for 274 Mb/s)	84.4 Hz
System and Equipment Degradation • Bandwidth limiting causing intersymbol interference • Nonlinearities and unbalance of power amplifiers • Matched filter mismatch due to band limiting • Carrier and sync loop jitter and bias	3.0 dB
Net Required C/kT	98.2 dB-Hz

The link analysis for the case of no rain shows a net system margin of +8.3 dB. This is achieved by using 12 m diameter earth terminals, a 12 ft diameter spacecraft antenna for receiving at 30 GHz, a 14 ft spacecraft antenna for transmitting at 18 GHz, and thermoelectric cooled paramp receivers of 120 K noise temperature. The spacecraft transmitter power provides 1 W rf output per data channel of 274 Mb/s.

For the case of uplink rain, the earth station selects the better of the diversity terminals and transmits at up to 60 W per channel rather than 20 W in clear weather. This maintains the net system margin at +8.3 dB.

For the case of downlink rain, the better of the diversity terminals is selected; however, no other change is made to the link parameters. The net system margin falls to +4.5 dB.

It should be noted that these margins are for the condition of a maximum antenna pointing error, a terminal located at ±3° off axis, and that a 3 dB equipment degradation factor is also included in the C/kT requirements. If a more conservative rain margin of 9 dB at 30 GHz and 6 dB at 18 GHz is used, then the system margin becomes 5.6 dB for uplink rain and 3.0 dB for downlink rain conditions.

3.2.2.2 Rain Attenuation for Trunking Link

The baseline concept for trunking communications would be implemented with dual space diversity earth terminals at each site. Thus the effect of rainfall attenuation is considerably less than that of the single terminal DTU systems. The detailed analysis of rainfall attenuation is discussed in subsection 2.3 and in Appendix A, whereas this section highlights the impact on trunking link application.

The trunking site location has a considerable impact on statistics of rainfall attenuation. The monthly average rainfall over a 30-year period for some of the large cities within CONUS is illustrated in Figure 3.2-5. Some areas have peak rainfall in the winter (San Francisco, Los Angeles) whereas others peak in the summer (Minneapolis, Chicago). The statistics also vary by year, and worst case years may have twice the rainfall of average years.

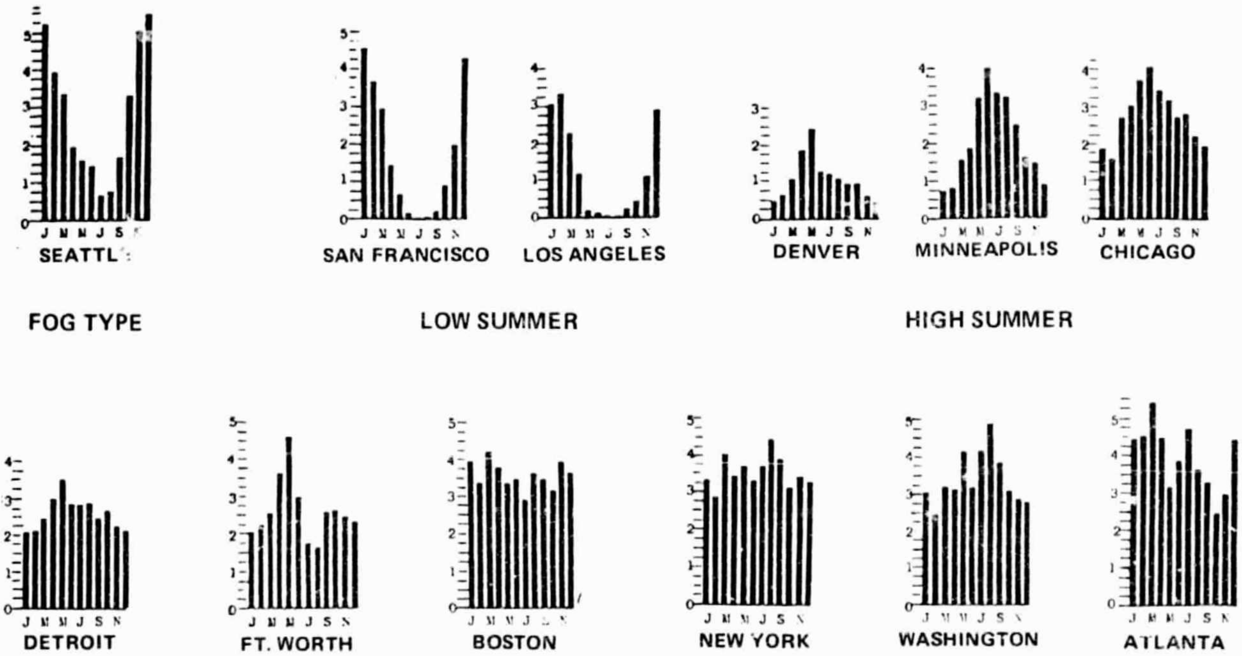
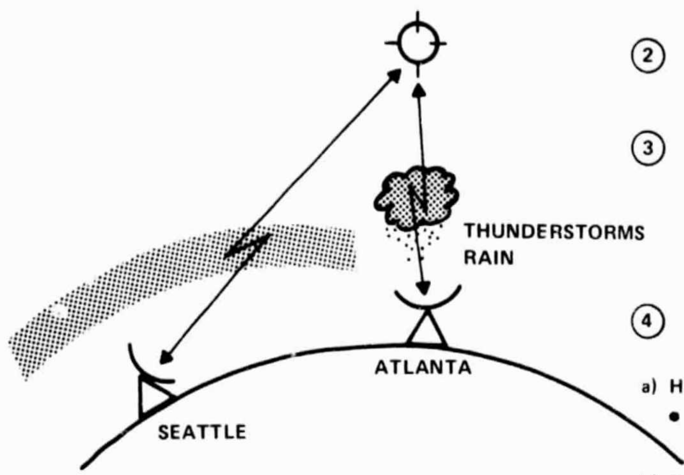


Figure 3.2-5. Normal Monthly Total Precipitation (Inches)

The type of rainfall is also significant. Some regions such as Seattle have large rainfall but it occurs over long periods of low rainfall rate. Rainfall in the Houston area consists of 55% by thunderstorm, which has significantly higher attenuation characteristics.

Several methods may be used to predict rainfall attenuation as shown in Figure 3.2-6. The view angle from earth terminal to spacecraft is another factor affecting path length through the raincloud coverage.



1. ESTABLISH CLIMATOLOGICAL RECORDS
   - RAINFALL STATISTICS OVER LONG PERIODS OF TIME
   - DETERMINE % RAIN BY THUNDERSTORM
2. GENERATE RAIN RATE MODEL
   - USE RICE-HOLMBERG TO DETERMINE % TIME A GIVEN RAINFALL RATE IS EXCEEDED.
3. DETERMINE ATTENUATION PER UNIT PATH LENGTH
   - USE OLSEN ET AL TO SET SPECIFIC ATTENUATION PER KILOMETER OF PATH LENGTH
   - DEPENDS ON DROP SIZE.
4. DETERMINE EFFECTIVE PATH LENGTH

a) HYDE MODEL
   - BASED ON COMSTAR MEASUREMENTS AT 19 & 29 GHz

b) EVANS MODEL
   - BASED ON ATS-5 AT 15 AND 34 GHz

c) CCIR MODEL
   - BASED ON EMPIRICAL RELATIONSHIPS

Figure 3.2-6. Methods for Determining Rain Attenuation

Future Systems Incorporated has prepared estimates of the rainfall attenuation values for a list of selected U.S. cities. A computer program was prepared to predict values for a satellite position of 100°W longitude and for 80° W longitude. The calculations are based on the CCIR model with relevant parameters adjusted for each city.

The predicted values at 18 GHz frequency for a spacecraft located at 100°W longitude are shown in Table 3.2-9. Values for both single terminal and dual diversity terminal (with separation of 8 km) are presented. In order to allow for uncertainties in the rainfall model and in diversity application it is recommended to add an additional transmission margin of several decibels for conservative concept evaluation. Table 3.2-9 shows that without terminal diversity and for 99.9% communications availability the range of attenuation for 10 selected cities (comprising the baseline network) is 3.4 dB in Los Angeles up to 12.4 dB in Houston. If 99.99% availability is desired then the attenuation range would increase to 7.9 dB in Los Angeles and 45.2 dB in Houston. The use of 8 km terminal diversity reduces the attenuation values to less than 5 dB for all 10 site locations.

Table 3.2-9. Rain Attenuation Statistics at 18 GHz

Trunking Sites	Annual Rainfall (mm)	% Rain by Thunderstorm	No Diversity		8 km Diversity	
			0.1%	0.01%	0.1%	0.01%
New York	1021	14%	6.3	23.5	3.0	4.1
Chicago	875	20%	5.4	24.1	3.8	5.0
Los Angeles	294	6%	3.4	7.9	2.2	3.3
San Francisco	496	6%	4.5	9.6	2.5	3.5
Washington, D.C.	988	19%	6.2	26.9	3.0	4.2
Dallas	820	50%	7.3	38.1	3.2	4.5
Houston	1224	55%	12.4	45.2	3.7	4.7
Minneapolis	659	15%	4.5	15.9	2.5	3.9
Atlanta	1228	40%	9.5	41.5	3.4	4.6
Denver	394	18%	3.6	12.5	2.2	3.7

The predicted values at 30 GHz frequency for a spacecraft located at 100°W longitude are shown in Table 3.2-10. It shows that without terminal diversity and for 99.9% communications availability the range of attenuation for 10 cities is from 10.0 dB in Los Angeles to 33.7 dB in Houston. If 99.99% availability is desired, then the values range from 22.3 dB in Los Angeles to 101.5 dB in Houston. The use of 8 km diversity terminals reduces the attenuation values to less than 4.4 dB for 99.9% availability and less than 6.1 dB for 99.99% availability.

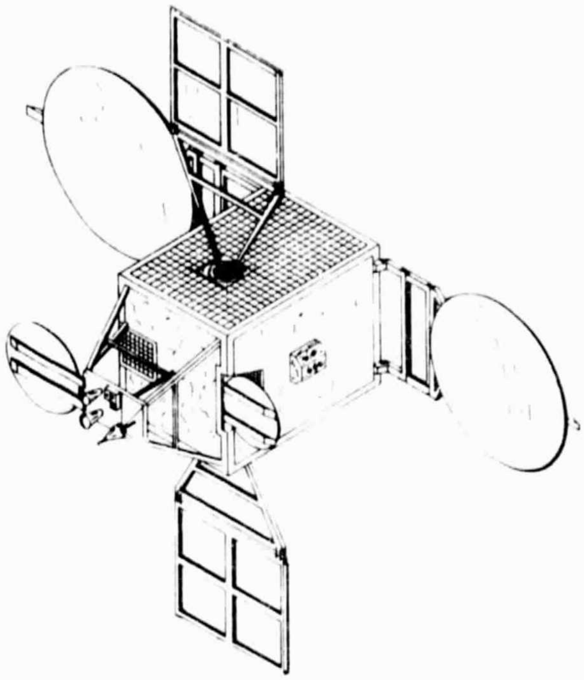
Table 3.2-10. Rain Attenuation Statistics at 30 GHz

Trunking Sites	Annual Rainfall (mm)	% Rain by Thunderstorm	No Diversity		8 km Diversity	
			0.1%	0.01%	0.1%	0.01%
New York	1021	14%	18.0	57.6	3.9	5.0
Chicago	875	20%	15.5	58.3	3.8	5.0
Los Angeles	2[illegible]4	6%	10.0	22.3	3.5	4.1
San Francisco	496	6%	13.1	26.6	3.7	4.2
Washington, D.C.	988	19%	17.9	64.7	3.9	5.1
Dallas	820	50%	20.6	87.4	4.0	5.7
Houston	1224	55%	33.7	101.5	4.4	6.1
Minneapolis	659	15%	12.9	42.2	3.7	4.6
Atlanta	1228	40%	26.5	94.4	4.2	5.9
Denver	394	18%	10.6	33.8	3.6	4.4

3.2.3 Spacecraft Segment

The configuration of the spacecraft for the baseline trunking system is largely determined by the requirements of CONUS coverage with multiple spot beams, communications subsystem with 90 channel filtered interconnect, 10-year on-orbit lifetime, and Shuttle compatible launch.

The baseline spacecraft design using three-axis stabilization is depicted in Figure 3.2-7, and additional layout details of the earth-facing view are shown in Figure 3.2-8. The baseline spacecraft has an on-orbit weight of 2417 lb, including sufficient fuel for the 10-year design lifetime. The length of the spacecraft is 21 ft and an additional 6.5 ft is required for a perigee motor. This combination utilizes about one-half of the length capacity of the Shuttle Orbiter payload bay.



ON-ORBIT WEIGHT	2420 lb
LENGTH	21 ft
MAXIMUM ARRAY POWER	1140 W
RF POWER	1 W/CHAN
ANTENNA	10 BEAMS, 0.3°
PERIGEE MOTOR	SPM-4
UNIT SPACECRAFT COST	$27 M

Figure 3.2-7. Spacecraft for Trunking System

Satellite Bus

Although the trend in satellites into the 1990 period would appear to be multifunctional in nature and could conceivably require construction in space, FACC recommends that the satellite bus for a first generation system be limited to Shuttle-only launches with no extravehicular activity required for deployment. The satellite bus is defined as (1) structure, thermal, and adapter subsystems; (2) electrical power subsystem; (3) telemetry, command, and ranging subsystem; (4) attitude control subsystem; and (5) propulsion subsystem.

a. *Structure/Thermal/Adapter Subsystem.* It is not anticipated that there will be any significant developments required in satellite structures to meet the requirements of the described systems. Advanced composite material technology is sufficiently developed that if weight should become a problem, these materials can be used in the basic satellite structure. For example, the antenna tower on the Intelsat V satellite is of GFRP construction. The major area of concern in this subsystem will be heat dissipation. Generally, thermal design maximizes the use of passive means where possible. Where required, louvres or heat pipes may be used.

b. *Electrical Power Subsystem.* Although thermal generators are an alternative source of electrical power for satellites, the baseline bus approach for this study is based on the use of solar arrays. Current technology used by FACC on Intelsat V yields a solar

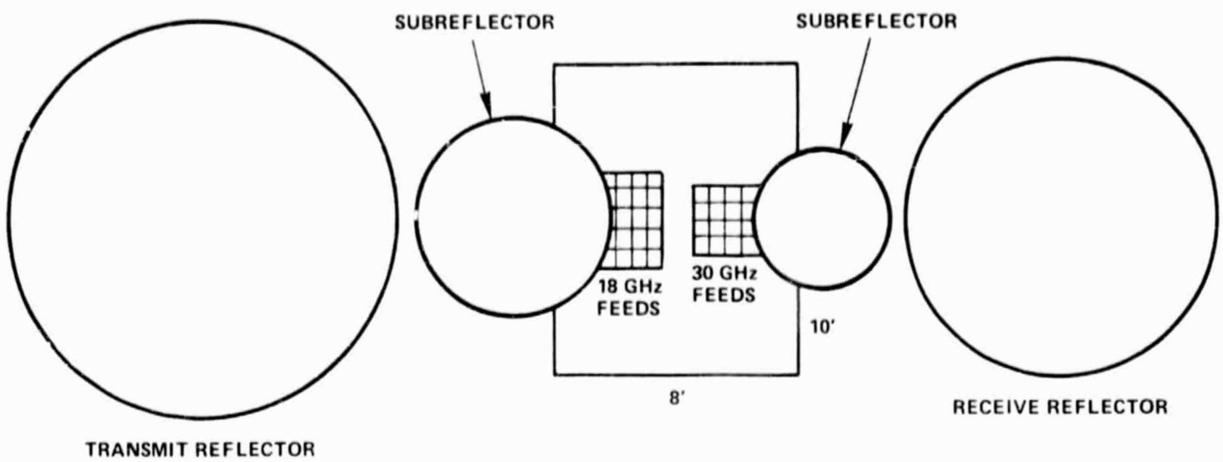


Figure 3.2-8. Earth Facing View of Spacecraft

array power output of 10 W/ft^2 at solstice at end of 7 years in orbit. Increased efficiency in solar cells is projected, from 11% in use today, to 16% in 10 years.

c. *Telemetry, Command, and Ranging Subsystem.* The TT&C subsystem would be compatible with known launch and range capabilities. The use of a satellite beacon to provide a reference for ground terminal EIRP control and TDMA frame synchronization is recommended.

d. *Attitude Control Subsystem.* Present technology permits the design and construction of three-axis-controlled satellites with life expectancies of 7 years and pointing accuracies in the range of 0.1° to 0.2°. With the introduction of multiple narrow spot beam and shaped beam antennas a higher degree of attitude stability and absolute pointing accuracy is required.

Of particular concern in these applications is a means for significantly improving yaw pointing accuracy without undue increases in system complexity and reduction in reliability. Current technology of the Intelsat V spacecraft has specified pointing error of ±0.2°.

The three-axis control for a first generation system would be a zero-momentum system consisting of three reaction wheels, three rate integrating gyros, and control electronics utilizing a microprocessor. Gas jets are used for momentum wheel unloading and for attitude acquisition. This type of attitude control system shows great promise or achieving the very precise attitude stability required for the performance of a variety of missions at synchronous altitudes. The combined use of earth sensors and rate integrating gyros with microprocessor filtering and control procedures represents a definite advance in the state of the art.

It is expected this design will achieve pointing accuracies of ±0.2° in pitch/roll and ±0.5° in yaw with altitude drift rates of less than 0.01°/hr about all axes. This design includes optimal sensing and signal processing techniques.

Attitude control of the satellite by means of a microwave position sensor should also be considered. The trend in attitude control is for greater accuracy and precision, which can be no better than that of the sensor. Earth and sun sensors seem near their inherent precision limit. Use of microwave direction finding techniques may be the most practical means.

The spacecraft and launch weight budget of Table 3.2-11 shows a total weight in the Shuttle Orbiter of 15,192 lb. This is about 25% of the 65,000 lb total weight capacity of the Orbiter. The costs of the Shuttle part of launch are proportional to the greater of the utilization of total weight or length capacity. It is seen that the baseline trunking configuration is length constrained rather than weight constrained in determining Shuttle cost allocation.

Table 3.2-11. Spacecraft and Launch Weight Budget

Item	Weight	
	(lb)	(kg)
Spacecraft Subsystems		
Communications	996	453
TT&C	50	23
Electrical power/electrical integration	270	123
Structure/thermal/mechanical integration	490	222
Attitude control/propulsion	230	105
Spacecraft dry weight	2,036	926
On-orbit fuel for 10 year life	381	173
Spacecraft launch weight	2,417	1,099
Transfer orbit system (SPM-4)	12,275	5,580
Cradle	500	227
Total weight in shuttle	15,192	6,905

A solar array power of 1140 W is required at the beginning of the 10-year on-orbit life in order to support the 90 W rf communications power. Twin solar paddle appendages would provide this power. A more complete breakdown of spacecraft power allocation is given in Table 3.2-12.

Table 3.2-12. Spacecraft Power Budget

Item	Power (W)
Power amplifiers (90 of 1 W rf)	400
Other communications subsystems	90
Other spacecraft subsystems	250
Battery charging	50
Total spacecraft load	790
Array design margin (5%)	40
Allowance for degradation of cells (10 years)	310
Total array output (BOL)	1,140

Spacecraft Communications Subsystem

A layout of the communications subsystem configuration for the baseline trunking system is shown in Figure 3.2-9. Input data signals are received from each of the trunking sites on 10 separate receive spot beams. Each site originates nine transmission carriers, each destined for a different city, and each containing up to 274 Mb/s of data in a QPSK modulation format. The total receive band available to each trunking site is 27.5 GHz to 30.0 GHz.

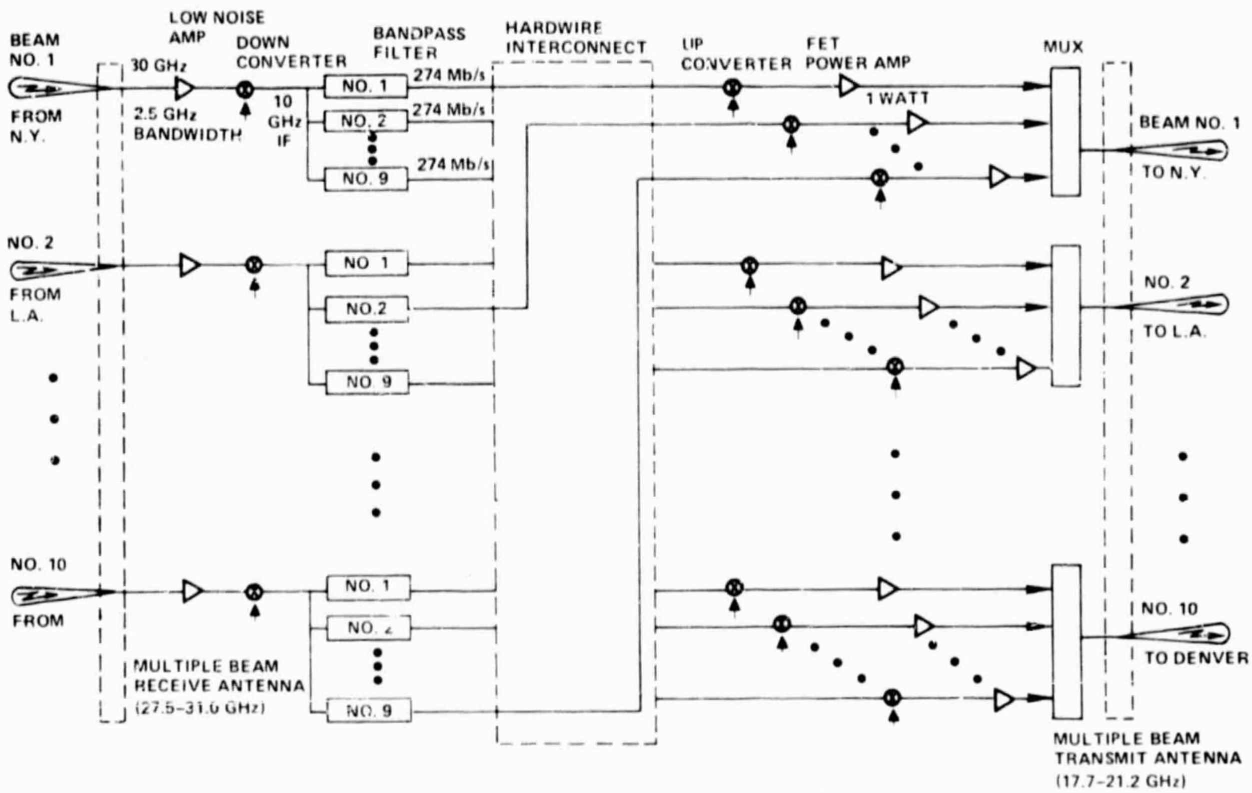


Figure 3.2-9. Communications Subsystem Configuration

The spacecraft receiver is a series of broadband low noise amplifiers that cover the 2.5 GHz receive bandwidth. The separate beam signals are then downconverted to an IF of about 10 GHz, and passband filters are used to obtain the channels destined for each city. The matrix combination of 10 trunking sites communicating to each other with full 274 Mb/s data rate capacity requires a hardwire interconnect of 90 filters to the appropriate output beams. The total throughput data capacity is about 25 Gb/s.

Each channel is upconverted, amplified with a 1 W rf solid-state transmitter, and multiplex combined on the appropriate downlink beam. There are 10 spot beams for the downlink and each is permitted full use of the frequency spectrum from 17.7 GHz to 20.2 GHz.

The baseline design incorporates equal data rate capability per channel; however, it is very feasible to have a variety of passband filter bandwidths in order to accommodate a skewed distribution of user requirements. The total data rate capacity of any beam cannot exceed

about 4 Gb/s, however, because of the limit on QPSK spectrum within the 2.5 GHz transmission bandwidth.

TT&C and Control Facility

All control facilities for a trunking satcom system could be located at a single site as shown in Figure 3.2-10. This facility would consist of (1) TT&C for control of housekeeping functions associated with spacecraft on-orbit positioning, antenna pointing, eclipse operations, etc, over a 10-year period; and (2) TT&C for control of the spacecraft communications configuration (if required). This optional feature is necessary if dynamic or daily or seasonal controls to wideband data link network distribution is required.

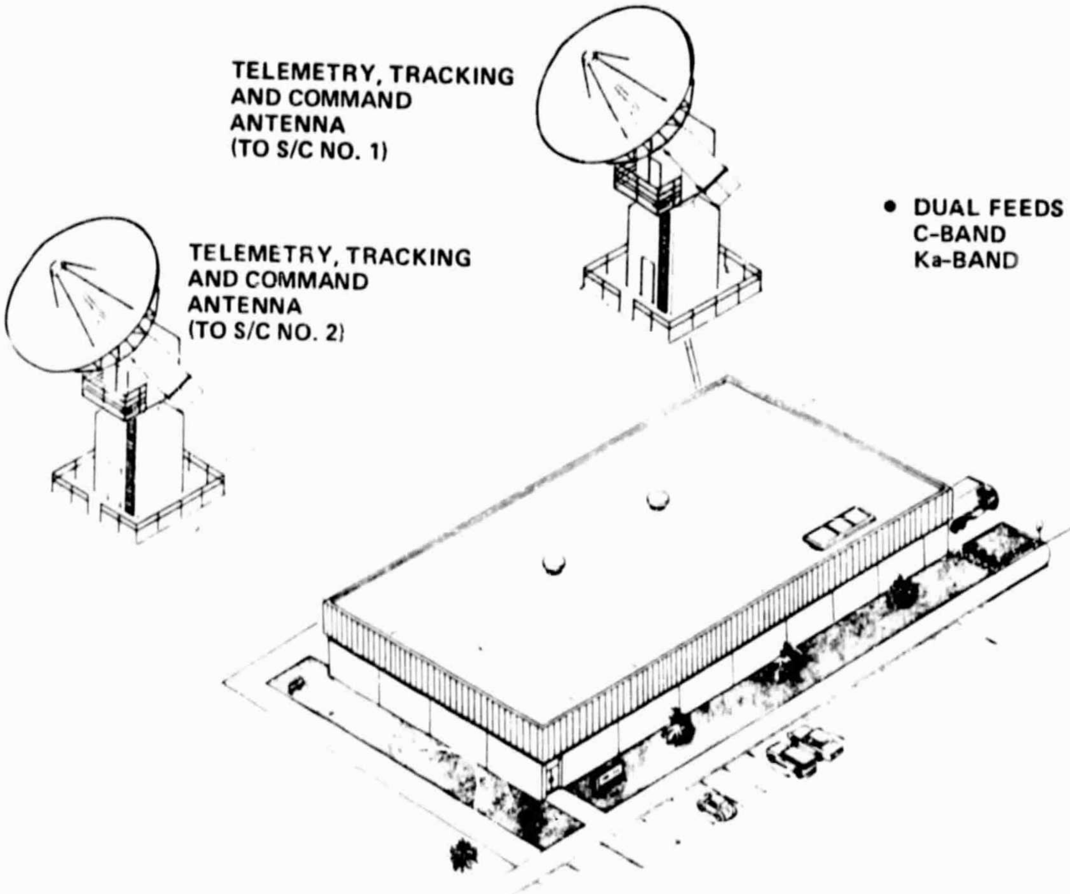


Figure 3.2-10. Master Control Facility and TT&C

A dual antenna configuration would probably be implemented if an operating and a backup spacecraft are required on orbit so that TT&C can be maintained to both spacecraft. A dual feed to permit TT&C operation at either C-band or K_A-band would be a desirable feature in order to minimize the effect of rain attenuation at 18/30 GHz.

Spacecraft Launch

The baseline trunking spacecraft has an expected initial on-orbit weight of 2417 lb. A perigee motor is required to take the spacecraft from the Shuttle Orbiter to synchronous equatorial orbit. This could be done by using an SSUS-A perigee motor or a four-tank spacecraft propulsion module (SPM-4) using liquid propellant. The SPM-4 design negates the need for the spacecraft apogee motor.

The integration of the baseline trunking spacecraft and an SSUS-A perigee motor within the Shuttle Orbiter payload bay is shown in Figure 3.2-11. The overall length of the combination is 28 ft, which is about one-half of the payload bay length capacity.

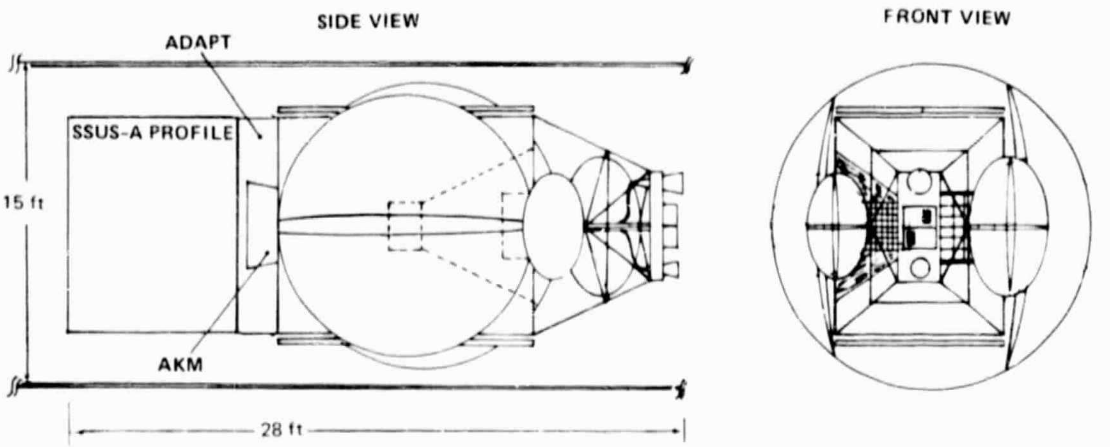


Figure 3.2-11. Integration of Spacecraft and SSUS-A

The spacecraft antennas are initially stowed in proximity to the body of the spacecraft such that the spacecraft fits within the 15 ft diameter envelope constraint of the Orbiter payload bay.

A concept of spacecraft and perigee motor deployment from the Space Shuttle Orbiter is shown in Figure 3.2-12.

C-2

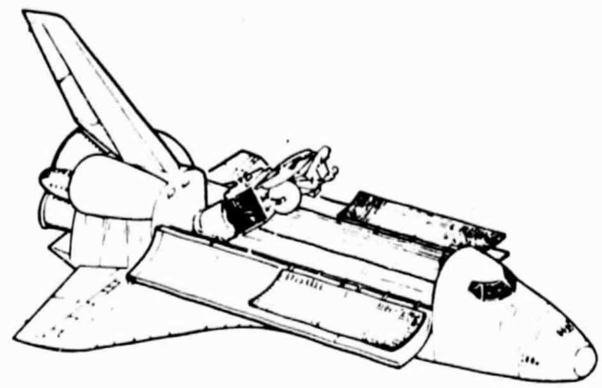


Figure 3.2-12. Spacecraft and SSUS-A Separating from Shuttle Orbiter

3.2.4 Earth Terminal Segment

The baseline trunking system concept incorporates the use of two earth terminals, separated by 8 km or more, at each trunking site as shown in Figure 3.2-13. The space diversity terminals are interconnected such that the one experiencing the lesser attenuation is utilized during rainstorm periods. The terminals are connected by microwave radio links operating at K_U-band or, as an alternate, buried cable or fiber optic lines could be used.

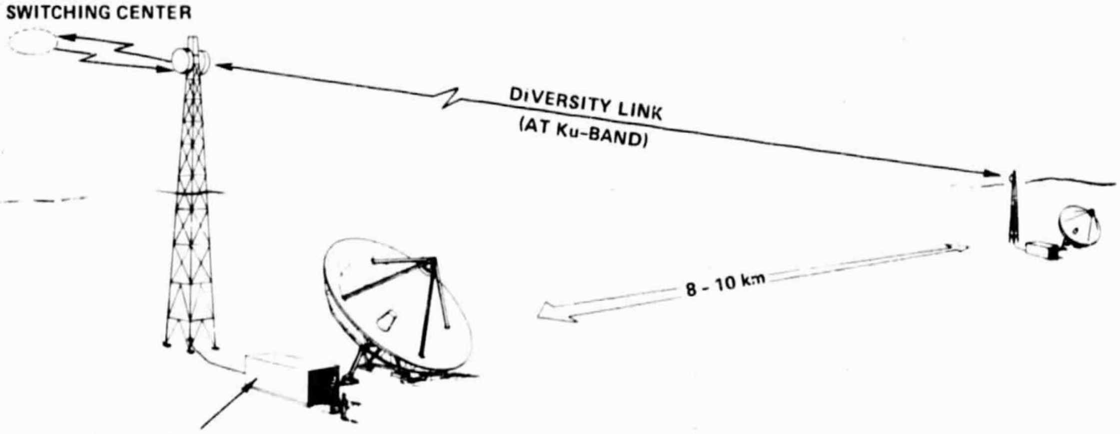


Figure 3.2-13. System Configuration of Trunking Site

All modems and diversity combining equipment are located at the main trunking terminal. The diversity system selects the best baseband data signal when receiving in heavy rain periods. The diversity terminal is designed for unattended operation in order to reduce costs.

The key parameters of the earth terminal are listed in Table 3.2-13.

Table 3.2-13. Earth Terminal Key Parameters

Operations

- Simultaneous transmit at 27.5 - 30.0 GHz and receive at 17.7 - 20.2 GHz band
- Dual polarization (horizontal and vertical)

Reflector

- 12 m diameter with 0.02 inch rms surface
- 69.0 dB transmit gain
- 64.6 dB receive gain

Pedestal/tracking

- Hour angle declination mount
- Movement of $\pm 10^\circ$ in hour angle and $\pm 5^\circ$ in declination
- Monopulse tracking with accuracy of 0.007°

Receiver

- Parametric amplifier with thermoelectric cooling (120 K noise)
- Clear sky noise temperature of 70 K

Transmitter

- Separate TWTA power amplifier per channel
- Variable power control over range of 20 - 60 W per channel

A dual polarization capability is employed in order to maximize the interbeam interference for trunking sites located in proximity.

A 12 m diameter reflector is utilized to obtain 69.0 dB transmit gain at 30 GHz and 64.6 dB receive gain at 18 GHz. An hour angle declination mount as shown in Figure 3.2-14 would be used to follow fixed adjustments to spacecraft on-orbit position. A monopulse tracking system is used to follow the daily stationkeeping changes in on-orbit position.

A cooled parametric amplifier with 120 K noise temperature would be used to enhance downlink receiving performance. The benefits of lower temperature receivers are negated by the high sky noise temperature associated with heavy rainfall conditions.

A summary block diagram of the trunking terminal configuration is shown in Figure 3.2-15, and additional detail is included in Figure 3.2-16.

Data to and from the switching center associated with each terminal site is received in a multiplex format with separate lines identified for each destination site. For the baseline design the data rate for each destination site may be up to 274 Mb/s.

In the transmit mode, each channel is separately transmitted by a variable power TWT amplifier. The output power will range from 20 W during clear weather up to 60 W during heavy rainfall periods. Spare amplifiers are included in the design to enhance reliability of operations.

A monitor of the spacecraft beacon frequency at 18 GHz may be used as a first order approximation to the transmit attenuation at 30 GHz.

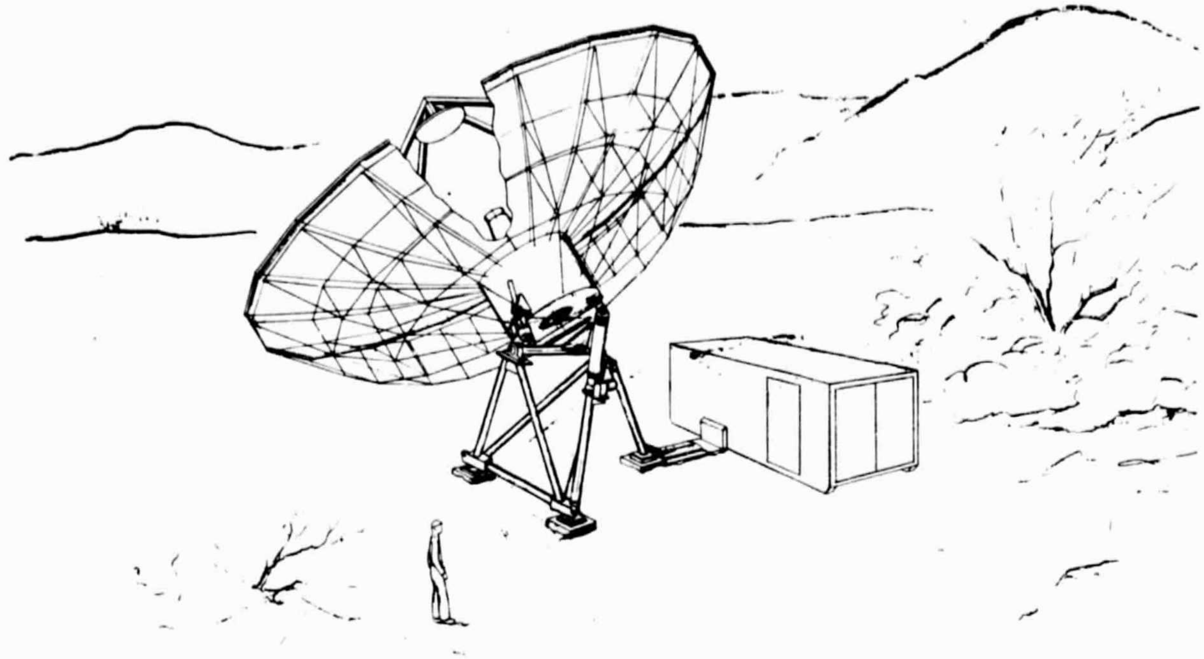


Figure 3.2-14. 12-Meter Trunking Terminal

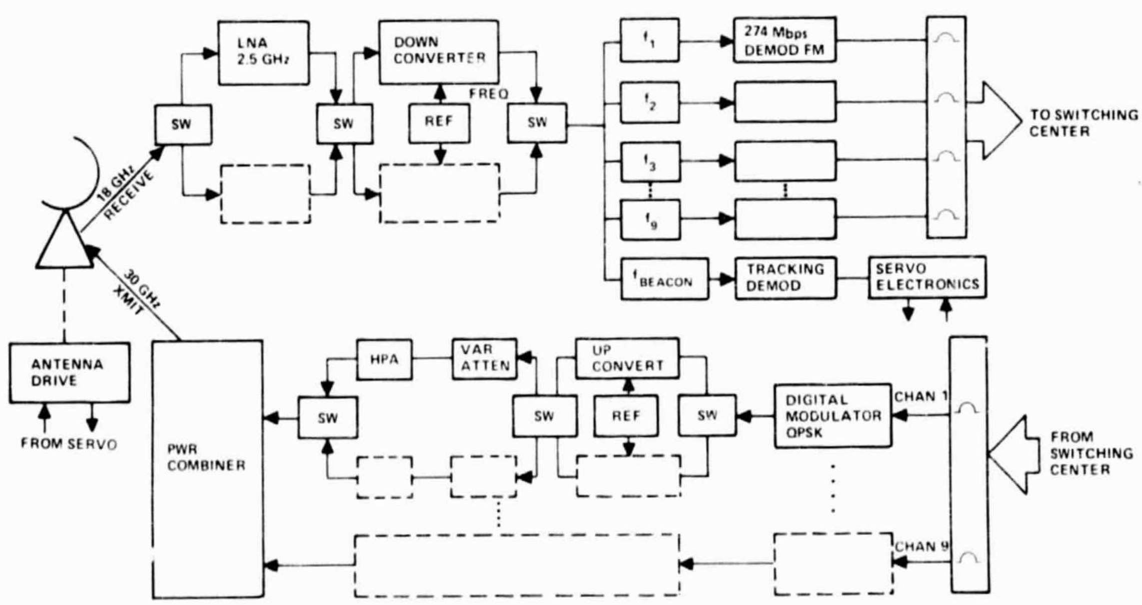


Figure 3.2-15. Trunking Terminal Configuration

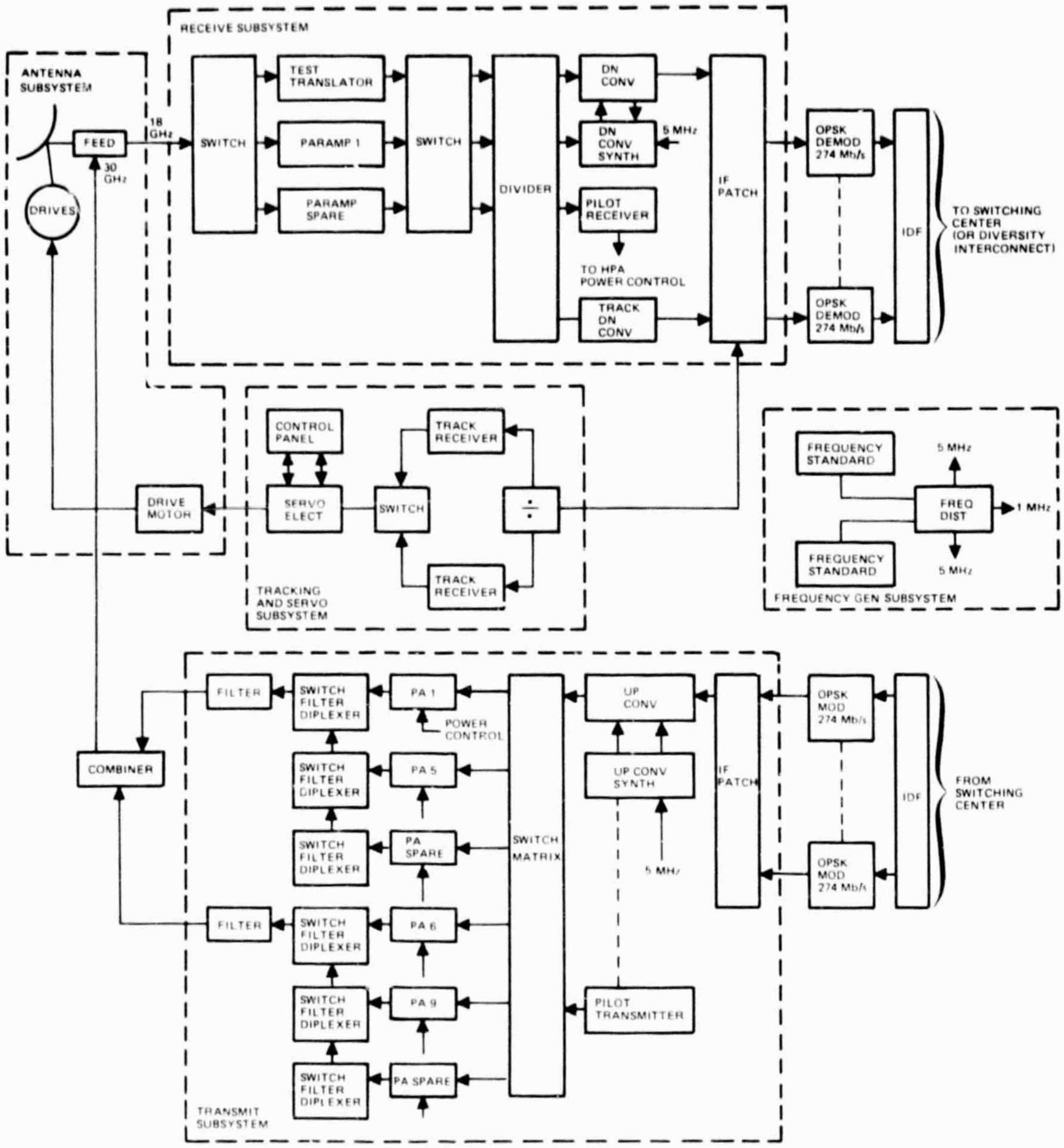


Figure 3.2-16. Block Diagram of Main Trunking Terminal

3.2.5 Costs of Baseline Trunking System

This section defines the guidelines for costing of a baseline satcom trunking system, determines spacecraft segment (spacecraft, launch, and TT&C) costs, earth terminal costs, and composite 10-year program costs. The baseline configuration, system costs, and circuit costs are summarized in Table 3.2-14.

Table 3.2-14. Trunking System Baseline Configuration

Baseline Design		
• 25 Gb/s system capacity		
• 10-site coverage with 0.3° antenna beams		
• FDM with 274 Mb/s per carrier		
• Solid-state amplifiers in spacecraft		
• Diversity earth terminals of 12 m diameter		
• No onboard switching or processing		
System 10 Year Costs		
• Spacecraft	$195 M	68%
• Launch and TT&C	$ 95 M	
• Earth terminals fixed	$ 78 M	32%
• Operations costs	$ 57 M	
Circuit Costs (satcom segment only)		
• Duplex 64 kb/s channel	$ 300/yr	
• Simplex 1.5 Mb/s channel	$3600/yr	

It is shown that if the number of sites in the trunking network is fixed at 10, then the spacecraft segment costs will constitute about 68% of the total 10-year system costs.

The satellite cost model utilized in this study is a slightly modified version of the U.S. Air Force Space and Missile Systems Organization (SAMSO) Unmanned Spacecraft Cost Model (USAF, 1977). This model is believed to be more accurate than the COMSAT modeling technique (Keisling et al - 1972). The USAF model uses parametric cost estimating relationships (CERs) that are based on logical cost generating variables (usually a physical or performance parameter of the spacecraft or spacecraft subsystem, based on engineering analyses rather than on a pure statistical basis). The data base for each subsystem usually contains a sample size of 16 or more spacecraft with measures of statistical fit having been performed to establish a reasonable valid range of the estimating parameter. The CERs were developed by least squares regression analysis by the line of best fit through the data.

3.2.5.1 Guidelines for Costing of Satcom System

The program implementation assumptions for costing of the 18/30 GHz direct-to-user satcom system elements are summarized in Table 3.2-15.

Table 3.2-15. Guidelines for Costing of Satcom Trunking System

System Costs

1. Base on 3 yr development period and 10 yr operational system life.
2. Base costs on 1978 dollars as reference.
3. Assume zero residual salvage value of satellites and terminals at end of 10 yr operational program life.

Satellite Costs

1. Assume four satellite program (refurbished qualification model and three flight units).
2. Assume all satellites manufactured within 4 years from program go-ahead.
3. Assume on-orbit TT&C from a new dedicated TT&C facility (two terminals) within CONUS. Spares and O&M are included.
4. Spacecraft to have 10-year design life with 10-year expendables.

Launch Costs

1. Assume shuttle launch, with full shuttle costs of $22 million in 1978 dollars.
2. Assume only three launches must be made over 10 year program and that no more than one satellite is launched per shuttle flight.
3. Assume insurance costs on successful satellite launch at 10% of satellite costs.

Earth Terminals

1. Include main terminal, diversity terminal, and 8 km wideband interconnect link.
2. Bit rates at multiples of standard PCM carrier rates by beam destinations to be provided to/from the switching center.
3. Earth terminals to have 15-year design life.
4. Spares and operations/maintenance are included. Design diversity terminal for unattended operation.

The system cost factors delineate a 10-year operation system life with no residual salvage value. If design obsolescence is precluded, it is likely that the terminals would really have a significant value at the end of the 10-year operating period and the remaining spacecraft capacity on orbit plus an unlaunched spare would also be of economic value.

The spacecraft costs are based on fabrication of three flight models and also refurbishing the qualification model of the development program in order to have a spare fourth spacecraft. The weight and costs of the spacecraft are based upon sufficient on-orbit attitude control fuel and sufficient equipment redundancy to meet a 10-year design lifetime.

3.2.5.2 Spacecraft Segment Costs

The spacecraft segment costs associated with the baseline trunking system consist of the spacecraft development and fabrication; TT&C terminal development, fabrication, and operation for a 10-year period; the pro rata share of the Shuttle launch costs; and perigee motors required to take the spacecraft from the low orbit of the Shuttle to a synchronous equatorial orbit.

Spacecraft Costs

The SAMSO-developed spacecraft cost model was used to determine the costs associated with the baseline parameters of the trunking spacecraft. This model was based upon cost data obtained from more than 16 satellite programs and has been progressively updated. A more complete description is given in the Appendix.

The initial steps require generation of orbit parameters and spacecraft subsystem weight and power. The spacecraft launch weight and perigee motor selection is then made. Spacecraft costs are then generated for an average spacecraft implementation using subsystem weights as the driving parameters. The key parameters for the baseline trunking configuration using FDMA are as follows:

Spacecraft Subsystem Weight	
Communications	996 lb
Structure/thermal	490 lb
TT&C	50 lb
Attitude control/propulsion	230 lb
Power (1140 W BOL)	270 lb
Launch Requirements	
Spacecraft launch weight	15,192 lb
Spacecraft perigee motor length	28 ft

The next step is to apply complexity factors to both the development and fabrication of each of the subsystems relative to the average case. This leads to the final cost estimating relationships (CERs) for both nonrecurring and recurring costs as shown in Table 3.2-16.

Table 3.2-16 Derivation of Spacecaft Costs Using FDMA

Subsystem	Basic CERs		Complexity Factors	Final CERs	
	Nonrecurring	Recurring		Nonrecurring	Recurring
Communications (996 lb)	18,682	9,235	1.71 NR 1.53 R	31,854	14,166
TT&C (50 lb)	1,395	745	1.22 NR 1.12 R	1,701	837
Power					
Basic (270 lb)	1,834	7,884	1.00 NR 1.00 R	1,834	1,084
Array Cells	380	304	1.32 NR 1.96 R	499	599
AACS (230 lb)	10,117	3,197	1.30 NR 1.10 R	13,162	3,507
Structure (490 lb)	4,697	881	1.35 NR 1.38 R	6,332	1,214
	SAMSO Cost Model			55,372	21,406
				Mgmt 16,912	5,352
				72,284	26,758
	$K (1978) all Figures				

The Shuttle pro rata costs are based upon the relative share of capacity utilization. The Shuttle is expected to have a total bay length of 60 ft and a total weight capacity of 65,000 lb. The base rates utilized for the Shuttle are as follows:

Complete Shuttle base rate = ($18.22M x inflation factor relative to 1975) + $4.3M = $27.3M

Pro rata Shuttle cost = (base rate x 1.33 or $36.25M) x pro rata based on 60 ft length (or 65,000 lb weight)

The baseline trunking system is length limited rather than weight limited in determining the launch vehicle cost allocation.

The baseline trunking spacecraft segment costs for FDMA configuration are summarized as follows:

Spacecraft	
Nonrecurring cost	**$72,283,000**
Recurring unit cost	**26,758,000**
Prototype refurbishment & support	**9,851,000**
Perigee Motor	
SPM-4 unit cost (or SSUS-A)	**$ 5,000,000**
Launch Vehicle	
STS pro rata unit cost	**$18,584,000**

The total satellite development nonrecurring costs are $72,283,000 expressed in 1978 dollar value. Each production model satellite would cost an additional $26,758,000.

The nonrecurring costs include a qualification model spacecraft. Refurbishing this unit to bring it up to flight qualified status is expected to cost an additional $9,851,000.

The unit pro rata share of Shuttle (STS) launch is $18,584,000, and the unit cost of a perigee motor is $5,000,000.

Total 10-year space segment costs are summarized in Table 3.2-17.

Table 3.2-17 Total 10-Year Space Segment Costs for Trunking System Using FDMA

Spacecraft (4)		
Development	$72,284,000	
Refurbishment of qualification model	9,852,000	$195,091,000
Three flight models @ $26.7 M ea.	80,274,000	
Profit and on-orbit incentives	32,681,000	
Launch (3)		
Shuttle pro rata at 28 ft length	55,753,000	70,753,000
Perigee motors (3)	15,000,000	
Spacecraft TT&C (10 years)		
Development	3,401,000	
Terminal and control center costs	10,107,000	23,610,000
Operations @ $1.0 M/year	10,102,000	
		$289,454,000

3.2.5.3 Earth Terminal Costs

The earth terminal costs represent about one-third of the overall system costs for the case of a 10-trunking-site (20-terminal) network.

A definition of the ground segment cost allocation between main terminal costs, diversity terminal costs, and costs allocated to the switching center is given in Figure 3.2-17. Some of the diversity terminal equipment (modems and comparator) is physically located at the main terminal, and some of the switching center costs (receiver/transmitter and modulation/demodulation equipment) are also located at the main terminal. The interface to the satcom segment is assumed to be nine PCM multiplexed data rates (one per destination city) at nominal rate of 274 Mb/s each.

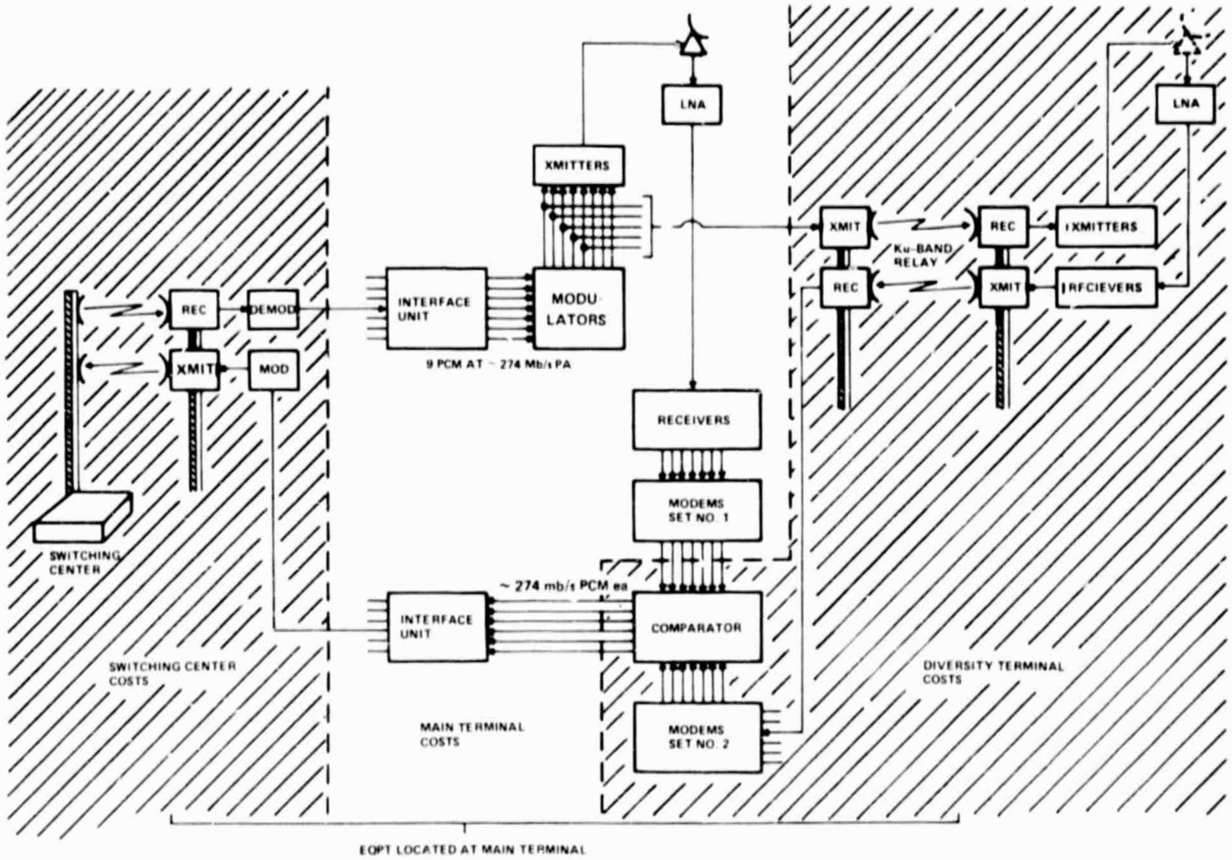


Figure 3.2-17. Definition of Ground Segment Costs

A breakdown of the predicted terminal costs for the baseline trunking system is given in Table 3.2-18. The costs are shown in 1978 value dollars for FDMA operation with nine rf carriers. A quantity discount factor of about 15% may be achieved if a production run of about 10 is awarded a single supplier.

The total fixed costs for a 10-site network is about $66,660,000 as shown in Table 3.2-19. An additional $56,640,000 per year is required over 10 years for operations/spares/maintenance of the user terminals.

Table 3.2-18. Cost Breakdown for Baseline Trunking Terminals Using FDMA

	Primary	Diversity
Antenna Subsystem: 12 meter reflector, pedestal, feed tracking	$ 950,200	$ 950,200
High Power Amplifier: 9 + 3 redundant, variable power of 20 to 60 W, includes switch/combiner	434,000	434,000
Low Noise Amplifier: 1 + 1 redundant, paramp with thermoelectric cooling	101,800	101,800
Frequency Translators: 12 upconverters and 12 downconverters (including redundant)	154,400	154,400
QPSK Modems: 9 + 3 redundant with step variable rates up to 274 Mb/s	180,200	–
Common Site Equipment (control/monitor, test, orderwire, freq. standard)	47,000	47,000
Other Site Equipment	373,800	337,600
Shelter	100,000	50,000
Installation & checkout	560,700	506,400
Initial spares	186,900	168,800
Land costs	Not included	
Diversity interconnect relay equipment (transceivers, towers, reflectors, & controls)	452,600	372,400
	$3,542,800	$3,123,300

*Based on 10 site/20 terminal buy as single contract

Table 3.2-19. Total Costs for 10-Site Terminals With Diversity Using FDMA

Fixed Costs	
Development Costs:	$11,819,400
Systems engineering, site surveys, training	
Ten main terminals	35,429,000
Ten diversity terminals	31,233,000
	$78,481,400
Annual Costs	
Full time attended operation at main terminal (4 shifts at 1.5 man level)	$ 5,364,000/yr
Remote operation at diversity terminal	
Maintenance	

3.2.5.4 Ten-Year Total Trunking System Costs

The total 10-year satcom system costs in 1978 value dollars for the baseline trunking system using FDMA is given in Table 3.2-20. The space segment cost including TT&C is projected at $289,000,000 whereas the procurement and operation of a 10-site earth terminal network is projected at $123,000,000.

Table 3.2-20. Ten-Year Trunking System Costs Using FDMA

Space Segment		
Spacecraft nonrecurring	$72,284,000	
Prototype spacecraft refurbishment	9,852,000	
Flight model spacecraft (3)	80,274,000	
Perigee motors (3)	15,000,000	$289,454,000
Pro rata STS launch (3)	55,753,000	
On-orbit incentives	32,681,000	
TT&C fixed and operations	23,610,000	
Terminal Segment (10 site)		
Nonrecurring	11,819,000	
Fixed hardware	54,842,000	$123,301,000
Operations and maintenance	56,640,000	
	$412,755,000	

A time spread of the trunking program costs is given in Table 3.2-21. The cost allocation is based upon the launch of two spacecraft in the initial year of operations and a replacement launch five years later. The installation of all earth terminals is assumed at the beginning of operations.

The cumulative cost buildup is illustrated in Figure 3.2-18. It is seen that 75% of the total 10 year costs are incurred by the end of the third year of operations because of the large initial fixed costs.

3.2.5.5 Equivalent Circuit Costs

The total 10-year costs for fixed investment and operation/main tenance of TT&C and a 10-site network was shown to be about $412 million. The maximum throughput capacity of the spacecraft is 25 Gb/s.

Because of the large fixed investment early in the program and receipt of revenue over a 10 year span it is expected that the cost of financing the fixed investment may be 50% of program costs.

The allocation of these costs over the maximum capacity results in the following circuit costs:

Table 3.2-21. Cost Spread for Trunking System Using FDMA

Program Element	Program Year												
	1	2	3	4	5	6	7	8	9	10	11	12	13
Spacecraft													
Spacecraft nonrecurring	48.9	24.9											
Spacecraft flight models (3)		32.1	32.1	16.1									
Prototype refurbish.				4.9	4.9								
3rd launch support								3.0					
Storage				0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
STS launch pro rata (3)	7.4	14.9	14.9			3.7	7.4	7.4					
Perigee motor (3)		5.0	5.0				2.5	2.5					
TT&C													
Nonrecurring	2.3	1.1											
Fixed hardware		5.0	5.1										
Earth Terminals (2)													
Nonrecurring	7.9	3.9											
Fixed hardware		33.3	33.3										
Operating Costs													
TT&C operation & maintenance				1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Terminals operation & maintenance				5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6
Spacecraft orbit incentives				3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3
Yearly Totals	66.5	119.7	90.4	31.1	15.0	13.8	20.0	23.0	10.1	10.1	10.1	10.1	10.1

Note: All figures in millions of dollars normalized to 1978 value

Duplex 64 kb/s channel (2 way)	\$300/yr
Simplex 1.5 Mb/s channel (1 way)	\$3600/yr

However, it should be noted that other factors must be added in order to determine the ultimate cost to the user. Other costs to be added include:

a. Cost of inflation
b. Switching center and "tail circuit" costs
c. Rate of return to communications carrier
d. Fill factors on circuit utilization

These costs, therefore, cannot be directly used to determine eventual tariffs.

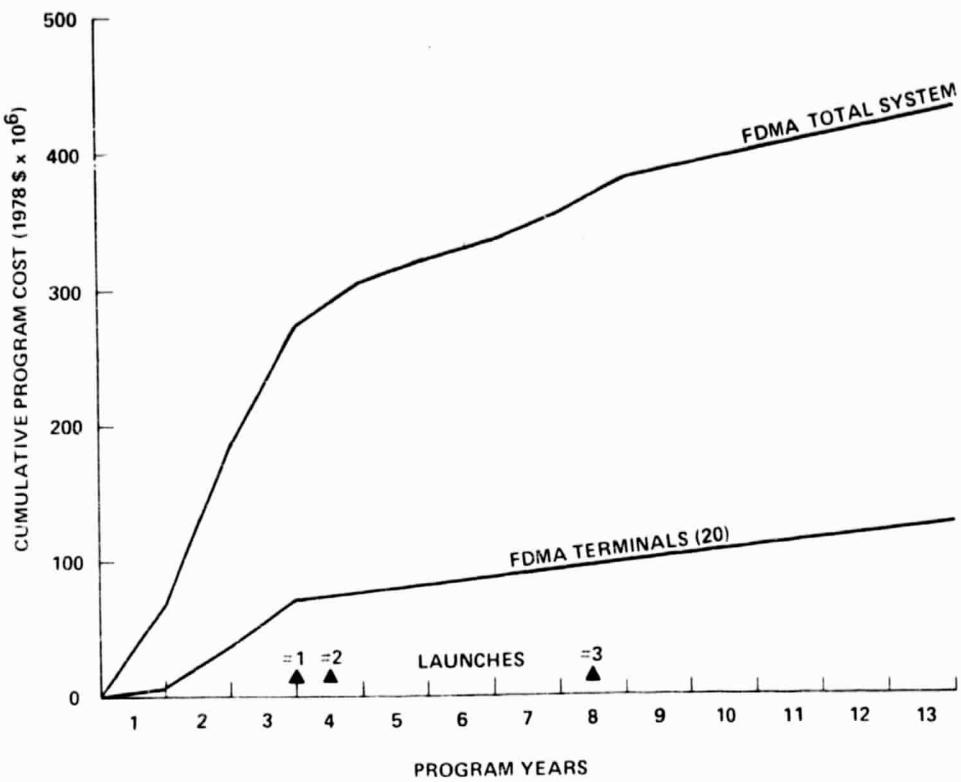


Figure 3.2-18. Trunking System Cumulative Costs

Subsection 3.3

Trunking Network Coverage and Spacecraft Antenna Limitations

It is generally desirable to have a large number of spot beams from the satellite to provide wide network coverage and hence reduce interconnect circuit path distance from user to trunking site. This section examines two of the factors that limit the number of spot beams.

The first concerns the projected traffic demand per city, which shows a large concentration of traffic in a small number of large city areas. Expansion to add the *n*th city, having a small demand, adds considerably to the spacecraft interconnect filtering matrix, which expands by the second power of the number of trunking sites.

The second limitation on number of spot beams is imposed by performance limitations of the spacecraft antenna: (1) the size of the antenna should be compatible with shuttle launch constraints, (2) the physical layout of feed positions is limited, (3) the amount of off-axis coverage is more than 10 beamwidths, and (4) the pattern sidelobes must be severely curtailed to prevent interbeam interference.

3.3.1 Network Coverage

Preliminary information on intercity traffic, based on current communications service and use, was supplied by ITT and by Western Union in November, 1978.

Table 3.3-1 shows that the selected 10-city configuration consisting of New York, Los Angeles, Chicago, San Francisco, Houston, Washington, Dallas, Minneapolis, Atlanta, and Denver would have an intercity communications demand that is about 10% of the total intercity traffic with CONUS. The table also shows that New York would originate and receive 21% of the traffic within the 10-city interconnect network whereas Denver would handle about 4%. A 10-spot-beam coverage of these sites is illustrated in Figure 3.3-1. The inner coverage ellipse represents the -3 dB pattern coverage and the outer ellipse the -20 dB pattern coverage. A combined isolation of about 25 dB is required through sidelobe cutoff and polarization diversity. The shaded beams would be of linear polarization and the unshaded of horizontal polarization.

Table 3.3-2 shows the projected intercity communications traffic for a 20-city network that makes up about 20% of the total CONUS use. The unbalance between New York City with 16% of the 20-city traffic and Buffalo with 1.5% is about 10:1. A 20-spot-beam coverage is illustrated in Figure 3.3-2. The potential interference between beams becomes apparent in the northeast region.

Table 3.3-3 shows intercity traffic for a 40-city network that makes up about 42% of total CONUS use. New York City would originate and receive 12% of the 40 city traffic whereas Salt Lake City would originate and receive only 0.8%. It is difficult to cover the 40 cities with individual spot beams; however, nearby cities could share a beam if they also share the 2.5 GHz of frequency spectrum. A 31-beam coverage pattern is illustrated in Figure 3.3-3.

Table 3.3-1. 10-Beam System Coverage

Rank	City/Area	Percent of Total CONUS	Percent of 10 Cities
1	New York	2.0	21.3
2	Los Angeles-Long Beach	1.7	17.8
3	Chicago	1.6	16.2
4	San Francisco-Oakland	0.8	8.6
5	Houston	0.7	7.4
6	Washington	0.7	7.0
7	Dallas-Ft. Worth	0.7	6.9
8	Minneapolis-St. Paul	0.5	5.4
9	Atlanta	0.5	5.0
10	Denver-Boulder	0.4	4.4
		9.6%	100%

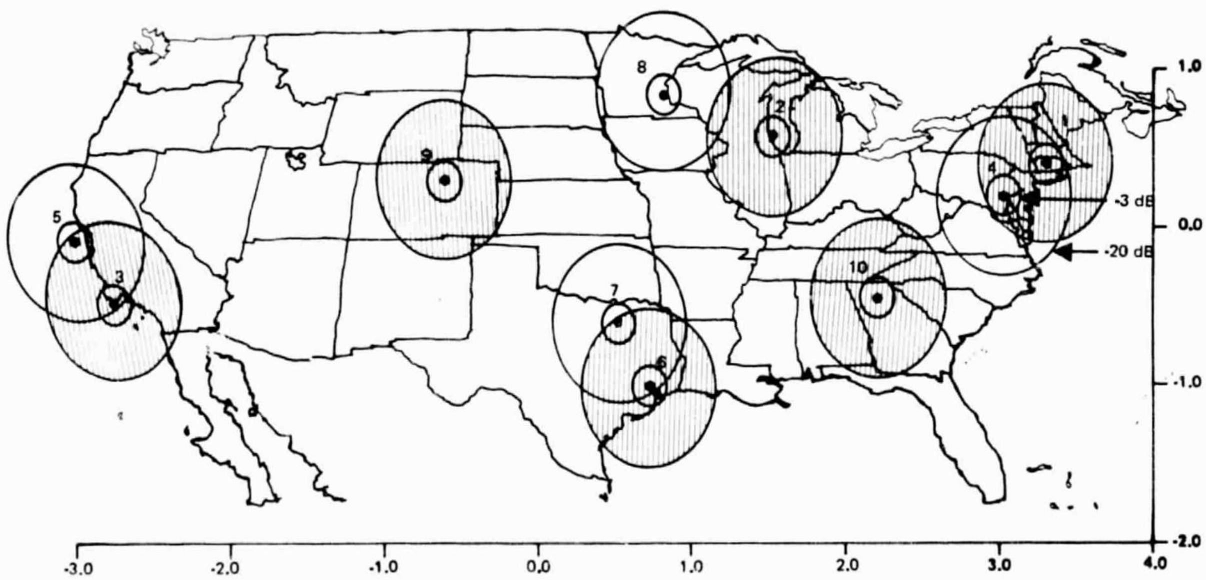


Figure 3.3-1. 10-Beam/10-Site Network Coverage

Table 3.3-2. 20-Beam System Coverage

Rank	City/Area	Percent of Total CONUS	Percent of 20 Cities
1	New York	3.16	16.2
2	Los Angeles-Long Beach	2.47	12.6
3	Chicago	2.30	11.7
4	Detroit	1.29	6.6
5	San Francisco-Oakland	1.13	5.8
6	Houston	0.99	5.0
7	Boston	0.96	4.9
8	Washington	0.95	4.8
9	Dallas-Fort Worth	0.92	4.7
10	Minneapolis-St. Paul	0.72	3.7
11	Atlanta	0.69	3.4
12	Pittsburgh	0.60	3.0
13	St. Louis	0.59	3.0
14	Denver-Boulder	0.58	3.0
15	Miami	0.47	2.4
16	Seattle-Everett	0.41	2.1
17	Phoenix	0.39	2.0
18	New Orleans	0.39	2.0
19	Portland	0.30	1.5
20	Buffalo	0.30	1.5
		19.6%	100%

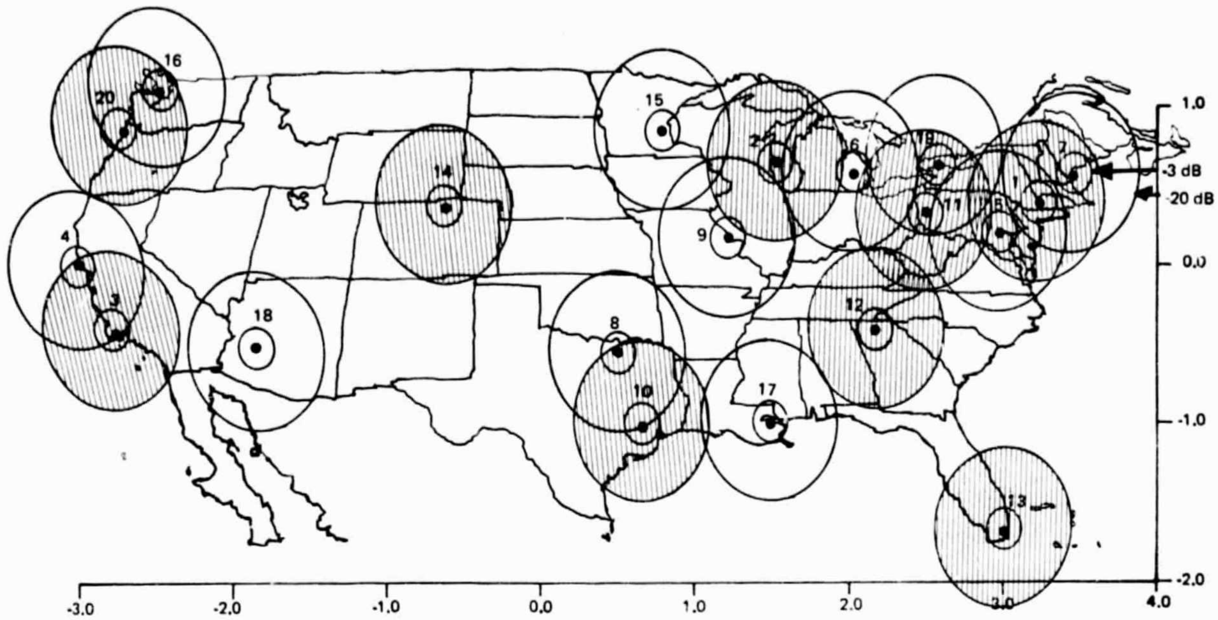


Figure 3.3-2. 20-Beam/20-Site Network Coverage

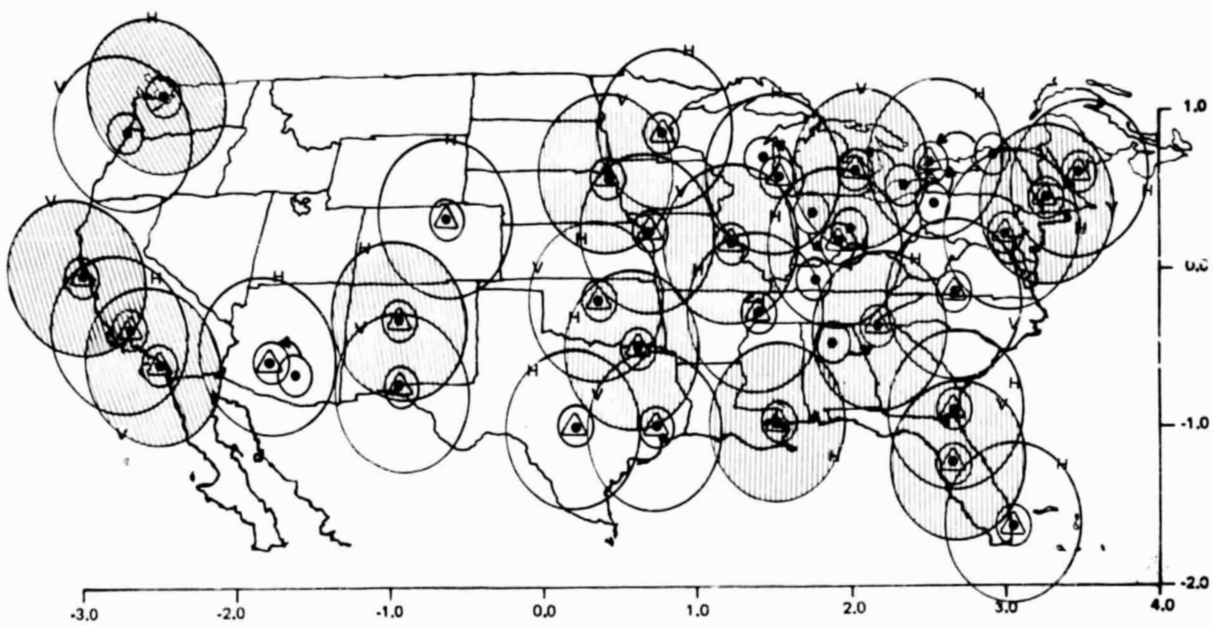


Figure 3.3-3. 31-Beam/40-Site Network Coverage

Table 3.3-3. 40-Beam System Coverage

Rank	City/Area	Percent of Total CONUS	Percent of 40 Cities
1	New York	5.11	12.1
2	Los Angeles-Long Beach	3.78	9.0
3	Chicago	3.43	8.1
4	Philadelphia	1.93	4.6
5	Detroit	1.89	4.5
6	San Francisco-Oakland	1.64	3.9
7	Houston	1.41	3.3
8	Washington	1.40	3.3
9	Boston	1.40	3.3
10	Dallas-Fort Worth	1.31	3.1
11	Minneapolis-St. Paul	1.02	2.4
12	Cleveland	0.96	2.3
13	Atlanta	0.96	2.3
14	Baltimore	0.96	2.3
15	Newark	0.90	2.1
16	Anaheim-Santa Ana	0.89	2.1
17	Pittsburgh	0.86	2.1
18	St. Louis	0.84	2.0
19	Denver-Boulder	0.83	2.0
20	San Jose	0.75	1.8
21	Miami	0.68	1.6
22	Cincinnati	0.65	1.5
23	Milwaukee	0.63	1.5
24	Kansas City	0.62	1.5
25	San Diego	0.61	1.5
26	Seattle-Everett	0.58	1.4
27	New Orleans	0.55	1.4
28	Phoenix	0.55	1.4
29	Indianapolis	0.52	1.3
30	Columbus	0.51	1.2
31	Tampa-St. Petersburg	0.49	1.2
32	Nassau-Suffolk	0.43	1.0
33	Buffalo	0.42	1.0
34	Portland	0.42	1.0
35	Memphis	0.41	1.0
36	Louisville	0.38	0.9
37	Hartford	0.38	0.9
38	Oklahoma City	0.36	0.8
39	Fort Lauderdale	0.36	0.8
40	Salt Lake City	0.35	0.8
		42%	100%

3.3.2 Spacecraft Spot Beam Antenna Limitations

Several design techniques were evaluated in order to select a baseline design for achieving multiple spot beams from the spacecraft. The major advantages and disadvantages of the reflector and lens type antennas are listed in Table 3.3-4.

Table 3.3-4. Alternative Spacecraft Antenna Implementation

Method	Major Advantages	Significant Disadvantages
Single Reflector	Simple optics. Planar feed array. Low mass.	Very long focal length. Larger feed array.
TEM Lens Antenna "Bootlace" type using stripline interconnections.	Compact configuration providing wide usable field of view, ie, great number of usable independent beams. Relatively large frequency bandwidth.	Very massive and complex assembly of many elements, each requiring precise fabrication and testing. Difficult to implement at higher frequency. Loss increases with frequency. Nonplanar focal surface.
Waveguide Lens Antenna "Bootlace" type, using straight compensated waveguide interconnections.	Compact, provides relatively large number of usable independent beams. Less mass than TEM construction. Lens elements easier to fabricate and have less loss.	Massive complex assembly. Waveguide dispersion limits frequency bandwidth. Nonplanar focal surface. Though stepping of lens surface reduces mass and may increase bandwidth, radiation performance is degraded.

In the design of a multiple spot beam antenna, the first task is to choose an antenna type that eliminates or minimizes those aberrations of greatest harm to specified performance goals. Usually the scannable antennas with the least aberrations are also those with the greatest number of design parameters and are thus structurally more complex. Properties of various available antenna types may be compared on this basis, as follows:

a. Single Reflector. The single reflector has only one design parameter available, namely the shape of the reflector. If the antenna engineer uses this parameter to eliminate spherical aberration, the resulting reflector is a parabola that has a perfect optical focal point; a feed at this location is normally defined as at zero scan. The paraboloidal pencil beam degrades rapidly with scan. For a large aperture with a half-power beamwidth of only 0.8°, first sidelobes may be -20 dB for zero scan; but for 9° (11.3 beamwidths) scan, the first sidelobes may degrade to a -5 dB and the second sidelobes to -10 dB. Also, nulls between sidelobes disappear. It may be that such severe constituent beam deterioration is intolerable

for forming spatially isolated and/or reconfigurable shaped beams.

b. Lens. FACC has studied a TEM lens with planar spherical surfaces, as well as a stepped waveguide lens. The TEM lens is free of spherical aberration and coma, which results in excellent scanning characteristics. Further application of the optical aberration basis for antenna design has been made at FACC by showing that using tapered illumintion feeds with the TEM lens permits achieving sidelobes below -30 dB for at least 21 beamwidths of scan. There is no doubt that the best shaped beam performance will be produced by the lens; however, spacecraft integration problems are increased.

c. Dual Reflector. A dual reflector system is a compromise selection. This system has two optical design parameters (two reflectors) and yet retains the mechanical simplicity of a reflector system. The classical Cassegrain dual reflector system has the form of a paraboloidal primary reflector and a hyperboloidal secondary reflector, which provides an exact correction for spherical aberration, but has the same coma as a paraboloid of the same focal ratio. However, one can design a dual reflector system to eliminate both spherical aberration and coma.

The disadvantage of a very long focal length associated with the single reflector type may be minimized by using a dual reflector approach (Figure 3.3-4), which was selected for the baseline trunking system design. Separate antennas are used for receiving at 30 GHz transmission band and transmitting at 18 GHz transmission band.

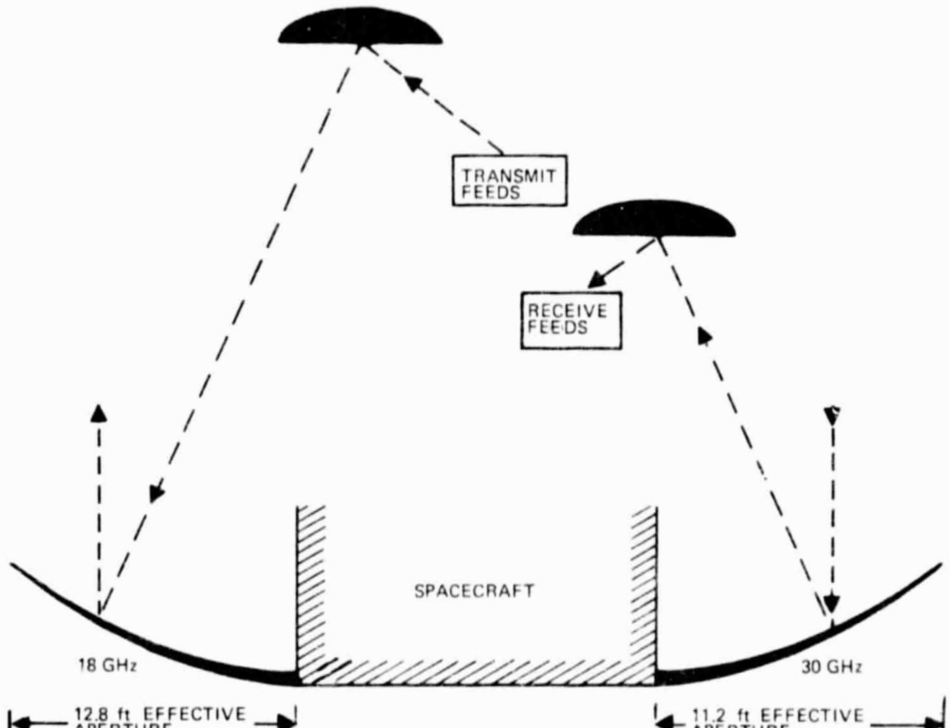


Figure 3.3-4. Relative Spacing of Antenna Elements

FACC has utilized its computer programs for evaluation of antenna performance for a dual reflector design. For the condition of a 14 ft diameter main reflector at 18 GHz an effective aperture of 12.8 ft is achieved. Predicted pattern performance is shown in Figure 3.3-5. This performance is that expected at the scan angle of ±3° from antenna boresight, which corresponds to the key coverage regions of the east coast or west coast cities. Better performance is obtained on axis.

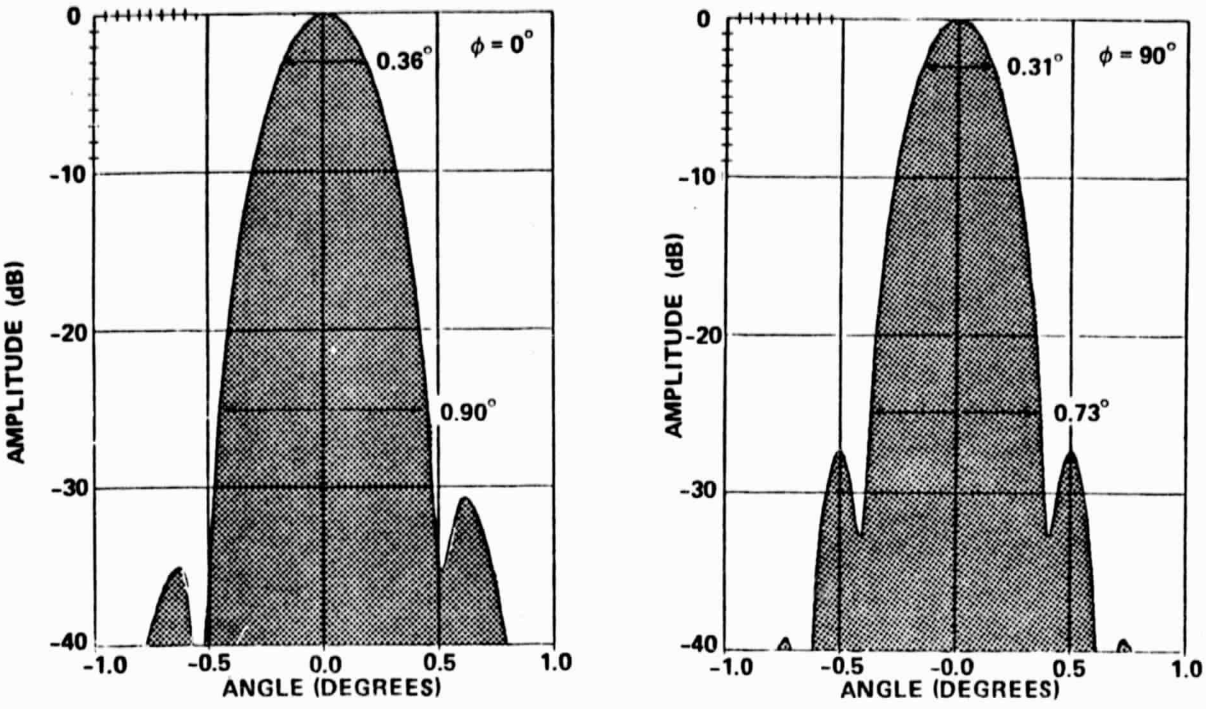


Figure 3.3-5. 18 GHz Antenna Pattern at 3° Scan Angle

It is shown that a half power beamwidth of 0.36° is predicted in one plane and 0.31° in the cross plane. The beamwidth performance at 25 dB down from peak of beam is 0.90° and 0.73°, which permits significant beam isolation.

In a similar manner the uplink performance at 30 GHz has been predicted. For the condition of a 12 ft diameter main reflector an affective aperture of 11.2 ft is achieved. Predicted pattern performance is shown in Figure 3.3-6. This performance is that expected at a scan angle of ±3° from antenna boresight.

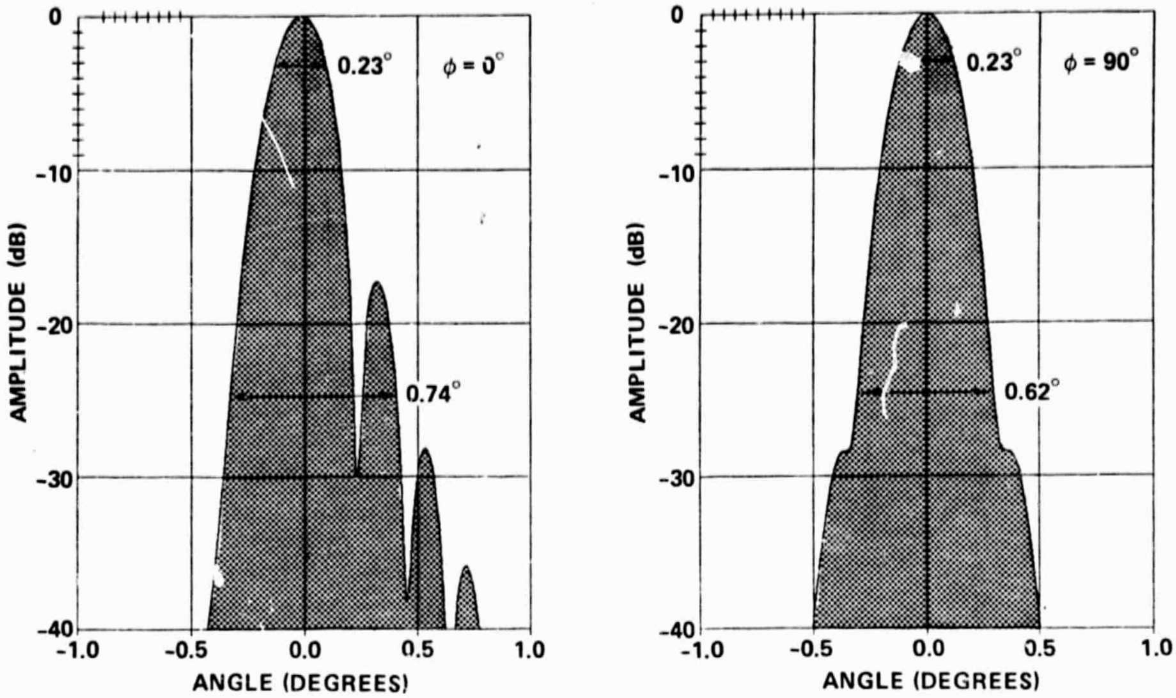


Figure 3.3-6. 30 GHz Antenna Pattern at 3° Scan

It is shown that a half power beamwidth of 0.23° is predicted in one plane and 0.23° in the cross plane. The beamwidth performance at 25 dB down from peak of beam is 0.74° and 0.62°. The impact of spacecraft pointing error stability must also be considered in evaluating interbeam isolation.

The predicted gain and associated losses for a dual reflector antenna are summarized in Table 3.3-5. It is noted that the off-axis degradation factor is expected to be less than 0.5 dB. It is recommended that the real performance of a dual reflector design be evaluated in model tests at an antenna range facility as well as flight test on orbit.

Table 3.3-5. Dual Reflector Antenna Gain and Loss Estimates

	18 GHz	30 GHz
Ideal Gain	+57.4 dB	+60.4 dB
Less Losses:		
Polarization Efficiency	-0.2	-0.2
Spillover efficiency	-1.0	-0.5
Aperture efficiency	-1.5	-2.0
Feed and line loss	-1.0	-1.5
Off-axis scan ($\pm3^\circ$) degradation	-0.5	-0.5
Net Gain – Peak	+53.2 dB	+55.7 dB
	(At Transmitter Port)	(At Receive Port)

Notes:

1. 18 GHz antenna has 14.0 ft dia main reflector, 12.8 ft projected aperture, and half power beamwidth of 0.31° at $\phi=90^\circ$ and 0.36° at $\phi=0^\circ$.
2. 30 GHz antenna has 12.0 ft dia main reflector, 11.2 ft projected aperture, and half power beamwidth of 0.23° at $\phi=90^\circ$ and 0.23° at $\phi=0^\circ$.

The physical dimensions of the multiple beam feeds and associated feed layout will restrict the proximity of beam spacing. A preliminary layout of feeds for the baseline trunking design for a 10-beam system is shown in Figure 3.3-7. The spacing limitation results in a performance to the New York and Washington, D.C. terminal sites that is about 0.5 dB down from the peak of the beam. The layout of feeds is for the condition of an 18 GHz antenna located on the west side of the spacecraft.

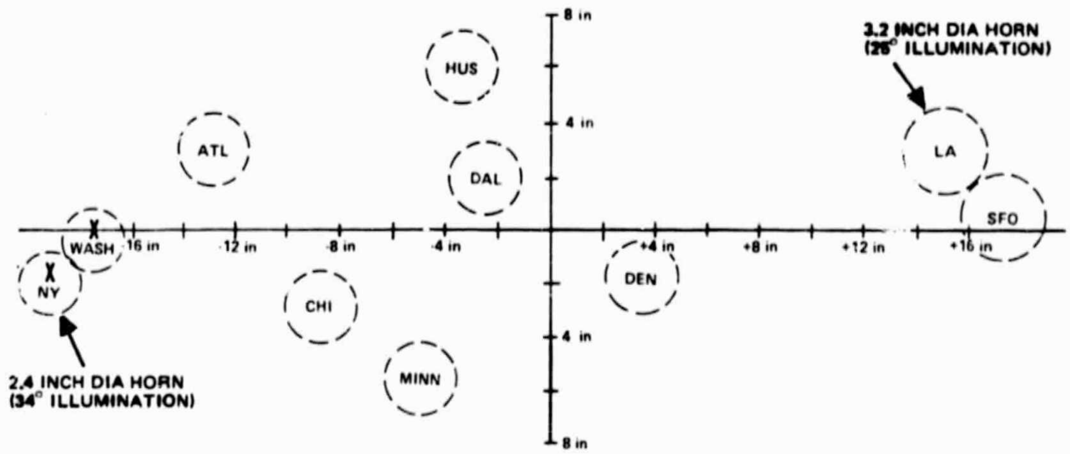


Figure 3.3-7. 18 GHz Feed Layout

Subsection 3.4

Alternative TDMA Trunking System

The use of time division multiple access (TDMA) modulation technique presents one of the key alternative concepts to the baseline FDMA system for trunking application. This subsection details tradeoffs, concepts, and costs of the TDMA approach.

3.4.1 Network Configuration

The relative advantages and disadvantages of TDMA systems in contrast to the baseline FDMA system of modulation are summarized in Table 3.4-1.

Table 3.4-1. Trunking System with TDMA

Parameters

- Ten-beam system with full 274 Mb/s interconnect requires 2.7 Gb/s burst rate
- QPSK modulation with spectrum width of 1.8 GHz per spot beam
- Uplink power control may be required to reduce adjacent-beam interference

Advantages

- Less satellite weight and power compared to multiple carrier per TWTA with FDMA because no backoff required
- Flexibility in allocating satellite resources between downlink beams to match traffic conditions yields more efficient satellite utilization

Disadvantages

- High peak power required from earth terminals
- High burst rate
- Precise time synchronization required
- Requirements for high-speed earth terminal data buffers
- Cost of earth terminal equipment higher

The main advantage of a TDMA system is that less satellite weight is required because the filtering in the spacecraft is considerably reduced. The spacecraft unit cost is also reduced to $19.3 million each (versus $26.7 million for FDMA). Also, the flexibility in allocating satellite resources to match a skewed traffic distribution is enhanced.

Disadvantages include the requirement for higher peak power from earth terminal transmitters, requirement for time sychronization and high speed data buffers, and requirement for a baseband switch in the spacecraft. Stationkeeping of the satellite must be fairly precise to minimize satellite motion. Otherwise, variations in propagation delay may cause problems with network synchronization. Buffers will be required at the ground terminals as part of the terrestrial network interface equipment to remove satellite motion effects.

An alternative TDMA concept consists of demodulating the signal in the spacecraft (Cuccia, Davies, and Matthews, 1977). The demodulated signal bursts, or packets, each have their own address codes which identify their destinations. The packets of data are placed in buffer storage and then read out in sequence by a digital switching matrix to the downlink beam. Each antenna beam has its own modulator and transmitter. This concept introduces a higher level of spacecraft technology, and 10-year reliability is compromised. It is not recommended for a first generation system configuration but is recommended for further study as a viable candidate for subsequent generation systems.

3.4.2 Spacecraft Configuration

The spacecraft transponder configuration for TDMA application is shown in Figure 3.4-1. Demodulation to baseband at 2.5 Gb/s is achieved for each of the 10 uplink beams. A baseband switch, operating at about 300 reconfigurations per second, is used to connect uplink and downlink beams to match the data frame format.

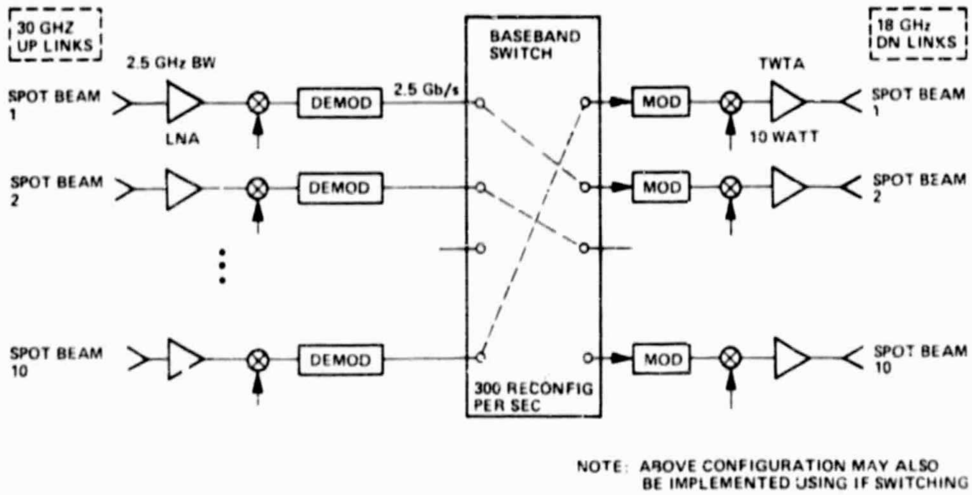


Figure 3.4-1. Spacecraft Transponder for Trunking System Using TDMA

Elimination of the baseline extensive filtering network reduces the communications subsystem weight to 454 lb, and the on-orbit spacecraft weight is 2661 lb as shown in Table 3.4-2. In addition, a smaller perigee motor is required (SSUS-D), and the total weight in the shuttle decreases to 9202 lb. This configuration incorporates an apogee motor as part of the spacecraft.

Table 3.4-2. Spacecraft and Launch Weight Budget (TDMA)

Item	Weight (lb)	Weight (kg)
Spacecraft Subsystems		
Communications	454	206
TT&C	50	23
Electrical power/electrical integration	223	101
Structure/thermal/mechanical integration	224	102
Attitude control/propulsion	267	121
Spacecraft Dry Weight	1,218	554
On-orbit fuel for 10-year life	276	125
Apogee motor fuel	1,168	530
Spacecraft Launch Weight	2,661	1,210
Transfer orbit system	6,041	2,746
Cradle	500	227
Total weight in shuttle	9,202	4,183

The total rf power is only 100 W, and the total spacecraft requires an end of life solar array power of 991 W. In order to accommodate solar cell degradation over a 10-year period on orbit, a beginning of life solar power of 1357 W is required.

The length of the spacecraft is about 21 ft with solar cells folded. The SSUS-D perigee motor adds an additional 7 ft of length to the overall stowed configuration.

3.4.3 Cost Analysis

The driving spacecraft cost parameters are as follows:

Spacecraft Subsystem Weight	
Communications	454 lb
Structure/thermal	224 lb
TT&C	50 lb
Attitude control/propulsion	267 lb
Power (1357 W BOL)	223 lb
Launch Requirements	
Spacecraft launch weight	9202 lb
Spacecraft & perigee motor length	21 ft

When the above parameters are applied to the SAMSO cost model as shown in Table 3.4-3 it is determined that a spacecraft nonrecurring cost (including qualification model) of $60 million is expected and that the recurring cost of each spacecraft is about $19 million. These values are less than those of the baseline configuration, which had development costs of $72 million and unit recurring costs of $27 million.

Table 3.4-3. Derivation of Spacecraft Costs Using TDMA

Subsystem	Basic Costs ($K)		Complexity Factors	Final Costs ($K)	
	Nonrecurring	Recurring		Nonrecurring	Recurring
Communications (454 lb)	11,596	5,080	1.90 NR 1.55 R	22,032	7,879
TT&C (50 lb)	11,395	745	1.32 NR 1.18 R	1,846	882
Power					
Basic 223 lb	2,141	1,086	1.00 NR 1.00 R	2,141	1,086
Array Cells	452	362	1.32 NR 1.96 R	596	708
AACS (267 lb)	11,233	3,600	1.38 NR 1.18 R	15,535	4,234
Structure (224 lb)	3,103	482	1.35 NR 1.38 R	4,177	664
	SAMSO Cost Model			46,326	15,453
				Mgmt 13,898	3,863
				60,224	19,316

The trunking TDMA space segment cost elements are summarized as follows:

Spacecraft	
Nonrecurring costs	$60,224,000
Recurring unit cost	19,316,000
Prototype refurbishment & support	8,363,000
Perigee Motor	
SSUS-D unit cost	$2,500,000
Launch Vehicle	
STS pro rata unit cost	$18,844,000

The associated earth terminal costs for a 10-site network are obtained using the terminal cost breakdown shown in Table 3.4-4 and are summarized in Table 3.4-5.

Table 3.4-4. Cost Breakdown for Baseline Tracking Terminals Using TDMA

	Primary	Diversity
Antenna subsystems: 12 m reflector, pedestal, feed, tracking	$ 950,200	$ 950,200
High power amplifier: 1 + 1 redundant	231,100	231,100
Low noise amplifier: 1 + 1 redundant, paramps with thermoelectric cooling	101,800	101,800
Frequency translators: two upconverters and two downconverters (incl. redund.)	47,000	47,000
QPSK Modems: 1 + 1 redundant with multiplexer and controller	261,900	–
Common site equipment (control/monitor, test, order wire freq. standard)	41,400	41,400
Other site equipment	317,500	265,100
Shelter	100,000	50,000
Installation and checkout	476,300	397,700
Initial spares	158,800	132,600
Land costs	Not included	
Diversity interconnect relay equipment (transceivers, towers, reflectors, and controls)	680,600	556,900
	$3,320,700	$2,727,900

*Based on 10 site/20 terminal buy as single contract

Table 3.4-5. Total Costs for 10-Site Terminals with Diversity Using TDMA

Fixed Costs	
Development Costs:	$10,896,400
Systems engineering, site surveys, training	
Ten main terminals	33,207,000
Ten diversity terminals	27,279,000
	$71,382,400
Annual Costs	
Full time attended operation at main terminal (4 shifts at 1.5 man level	$ 5,484,000/yr
Remote operation at diversity terminal	
Maintenance	

The combined system costs for a 10-year operating period are listed in Table 3.4-6. The total space segment costs of $239 million constitute 65% of the total program cost. The total earth segment cost for a 10-site network (20 terminals) including operations and maintenance is expected to be $126 million, which is 35% of total program costs.

Table 3.4-6. Costs for Trunking 10-Year System Using TDMA

Space Segment		
Spacecraft nonrecurring	$60,224,000	$239,484,000
Prototype spacecraft refurbishment	8,363,000	
Flight model spacecraft (3)	57,948,000	
Perigee motors (3)	7,500,000	
Pro rata STS launch (3)	56,532,000	
On-orbit incentives	25,307,000	
TT&C fixed and operations	23,610,000	
Terminal Segment (10 sites)		
Nonrecurring	10,896,000	$126,222,000
Fixed hardware	60,486,000	
Operations and maintenance	54,840,000	
	$365,706,000	

The cost spread by program year, including a 3-year development period, is shown in Table 3.4-7. A plot of the trunking TDMA cumulative costs is shown in Figure 3.4-2.

It is seen that 78% of the total costs are incurred before the end of the sixth program year (third year of on-orbit operations) whereas revenue is expected to start at a low level and increase over the operating period. This means that a major expense is incurred for the financing of the net investment.

Table 3.4-7. Cost Spread for Trunking System Using TDMA

Program Element	Program Year												
	1	2	3	4	5	6	7	8	9	10	11	12	13
Spacecraft													
Spacecraft nonrecurring	40.1	20.1											
Spacecraft flight models (3)		23.2	23.2	11.6									
Prototype refurbish.				4.2	4.2								
3rd launch support								3.0					
Storage				0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
STS launch pro rata (3)	7.5	15.2	15.2			3.8	7.6	7.6					
Perigee motor (3)		2.5	2.5				1.3	1.3					
TT&C													
Nonrecurring	2.3	1.1											
Fixed hardware		5.0	5.1										
Earth Terminals (10 Site)													
Nonrecurring	7.3	3.6											
Fixed hardware		30.2	30.2										
Operating Costs													
TT&C operations & maintenance				1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Terminals operation & maintenance				5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
Spacecraft orbit incentives				2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Yearly Totals	57.3	100.9	71.2	25.0	13.4	13.0	18.1	21.1	9.2	9.2	9.2	9.2	9.2

Note: All figures in millions of dollars normalized to 1978 value

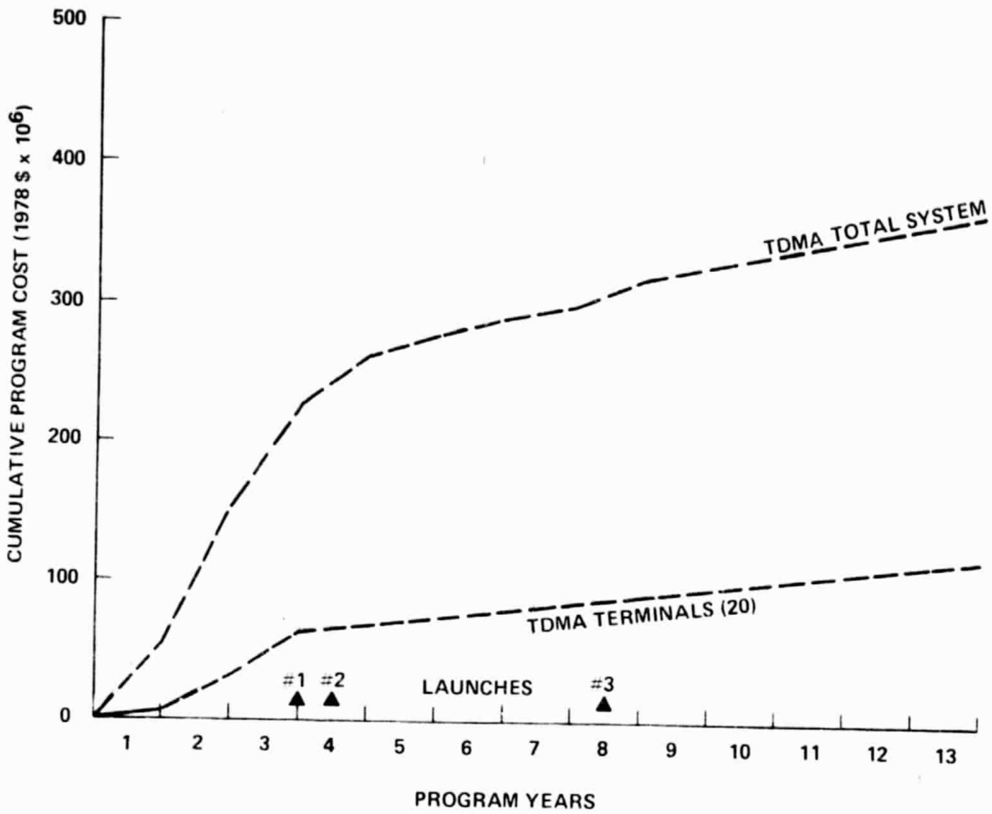
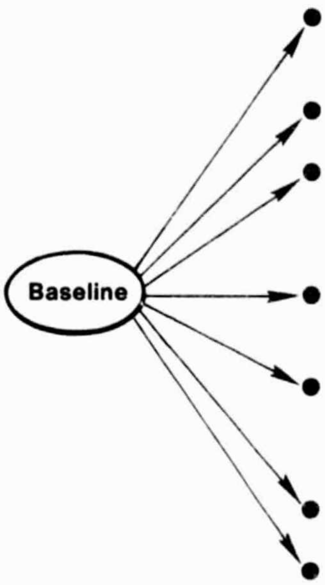


Figure 3.4-2. Cumulative Costs for Trunking System Using TDMA

Subsection 3.5

Other Tradeoff Alternatives to Baseline Trunking Configuration

The roadmap of design alternatives for the baseline DTU system configuration was previously shown in Figure 3.1-1. The baseline FDMA system and an alternate TDMA system were previously described in subsections 3.3 and 3.4. This subsection examines the performance and cost tradeoffs for other alternative candidate system configurations. Potential variances to the baseline are listed in Figure 3.5-1 and Table 3.5-1.



Increase number of sites	-	Increased complexity of S/C multiplexing but tails circuit costs reduced
Increase system capacity	-	User demand may not exceed 25 Gb/s for 1st generation
Nonuniform channel capacity	-	Recommended for more efficient match to user needs
	-	New York beam traffic limits system
TDM modulation	-	High-capacity system requires 2.5 Gb/s modulators and high-peak power transmitters
Eliminate diversity terminal	-	Saves $3.2 M per site but communications availability decreased or space segment costs increased significantly
Increase S/C power	-	Becomes cost effective for large number of earth terminals
Collector SATCOM links within beam	-	May be included to reduce tails circuit costs

Figure 3.5-1. Trunking System Alternatives

The tradeoff of performance and cost for some of these alternatives is described in this section. The use of computer programs for optimization of spacecraft and earth terminal configuration to meet specific performance objectives is illustrated in Figure 3.5-2. The input parameters to a specific analysis include the desired on-orbit lifetime, number of spot coverage beams, data rates, link margin requirements, etc. Certain design constraints are also imposed. These would include shuttle bay diameter, spectrum allocation bandwidth, on-orbit geostationary slot position, perigee motor capacities, and technology limitations.

Table 3.5-1. Options to FDMA Trunking System

Network/Performance	Spacecraft	Ground Terminal
Increase number of trunking sites.	Larger array and increased rf power	Eliminate diversity terminal
Allocate channel bandwidth in proportion to communications requirements of each site.	Multiple channel per TWTA	Reduce diameter to 10 meters Increase diameter to 17 meters
Lower communications availability to 99.5% or increase to 99.99%	Odd-even channel combining	Fixed transmitter power
8-psk modulation for spectrum efficiency	Unfurlable antennas of 20 ft dia or more for higher EIRP	BPSK modems
Include TDMA among smaller terminals within ±100 miles of the trunking terminal		Cryogenic cooled paramp

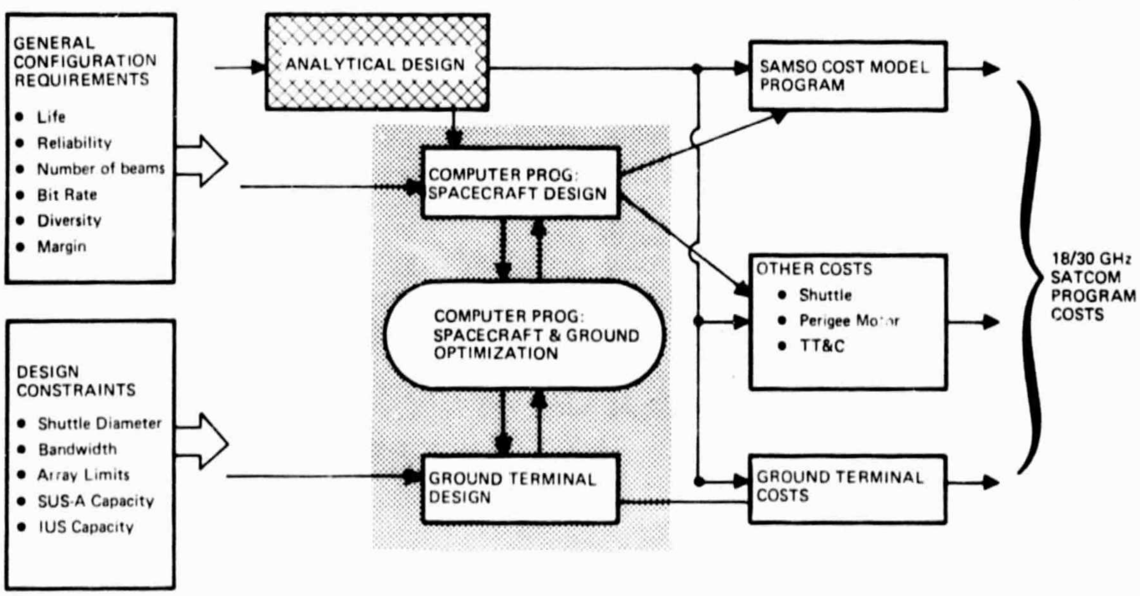


Figure 3.5-2. Design/Cost Model Interaction

3.5.1 Alternate Configuration: Increased Number of Trunking Sites

If the same 274 Mb/s between all sites is retained as a requirement, and if the number of trunking sites is increased to 16, then the total throughput capacity of the system increases from 25 Gb/s to 65 Gb/s as was shown in Figure 3.5-1. The number of 16 sites is chosen because it permits the full use of the available 2.5 GHz spectrum by each trunking site, ie, 4.1 Gb/s with QPSK modulation. The increased number of sites reduces the distance from users to the switching centers and hence "tails circuit" costs are reduced.

The impact on the spacecraft is a greatly increased complexity of filtering and the number of power amplifiers (one per channel) increases up to 240. The increased power and weight of the spacecraft is expected to increase space segment costs by about $84 million. The $55 million costs of six additional diversity sites must also be included; however, a considerable improvement in system performance is obtained.

The tradeoff illustrated in Tables 3.5-2 and 3.5-3 shows the impact of increasing the number of trunking sites to 20 while keeping the spacecraft throughput capacity fixed. Both FDMA and TDMA modulation techniques were examined. The tradeoff shows that a 20-beam TDMA system is feasible, although system costs increase by $179 million. A 20-beam FDMA system would require extensive spacecraft filtering, which would drive the on-orbit weight to about 7800 lb, which exceeds the capacity of the IUS perigee motor.

Table 3.5-2. Modification to Number of Trunking Sites for Fixed Capacity

Modification: Examine costs for increase to 20-beam system
Total throughput capacity of spacecraft is fixed

System Cost Impact	10-Beam FDMA	10-Beam TDMA	20-Beam FDMA	20-Beam TDMA
Program				
Space segment cost	$289M	$239M	Spacecraft weight >7800 lb	$311M
Terminal costs	$136M	$127M		$234M
Total costs	$425M	$366M		$545M
Development:	Ref.	Development required		Development required

Conclusions:

- Use of TDMA reduces program costs but technology development required
- For large number of beams TDMA is better choice
- Use of multiple beams also reduces "tail" circuit costs

Table 3.5-3. Modification to Number of Trunking Sites and Capacity

Modification	Network/Performance Impact	Space Segment Impact
Maximize system data rate capacity by increasing number of trunking sites to 16	Full use of 2.5 GHz spectrum per spot beam Expanded network coverage with full 274 Mb/s interconnect System capacity increases from 25 Gb/s to 65 Gb/s Decentralization of trunking sites	Increased complexity of spacecraft interconnect and multiplexer Active spacecraft power amplifiers increase from 90 to 240 Spacecraft solar array power increases by ~ 1140 W Total launch weight increases by ~ 3000 lb Space segment costs increase by ~ $84 million
		Ground Segment Impact
		Cost for 6 additional diversity sites is ~ $55 million Tail circuit costs are reduced

3.5.2 Alternate Configuration: Nonuniform Allocation of Bandwidth

It was shown in subsection 3.2 that the traffic demands per trunking site may have a wide range rather than the uniform distribution of the baseline design. The impact of allocating a spacecraft channel capacity in proportion to the demand requirements of each site is illustrated in Table 3.5-4.

Table 3.5-4. Modification for Nonuniform Allocation of Bandwidth

Modification	Network/Performance Impact	Space Segment Impact
Allocate channel capacity in proportion to demand requirements of each site	Provides better match to real system demands Full spectrum capacity for New York beam limits the system System capacity ranges from ~ 4 Gb/s (NY) to ~ 1 Gb/s (Denver) Total system capacity remains at ~ 24 Gb/s	Nonstandardization of filters and power amplifier levels in spacecraft Total spacecraft power remains the same Space segment costs increases by ~ $5 million
		Ground Segment Impact
		For 3 sites at 4 Gb/s, 4 at 2 Gb/s and 3 at 1 Gb/s Antenna performance may be reduced by 2 dB to 5 dB for low capacity sites for a savings of about $5 million

The impact on network and performance is that this modification does provide a better match to real system demands. The full spectrum capacity for the New York City beam is 4 Gb/s using QPSK modulation and 2.5 GHz bandwidth. The data rate to New York City may be four times that to Denver.

The impact on the spacecraft is a requirement for nonstandardization of filter bandwidths and power amplifier levels. The total spacecraft power remains constant because total system throughput capacity is relatively unchanged. It is expected that space segment costs would increase by about $5 million.

The costs of each trunking site would also vary with the data rate. As an example for the 10 beam system, three sites could communicate at 4 Gb/s, four at 2 Gb/s, and three at 1 Gb/s.

The significant performance advantages and minimum cost impact lead to the conclusion that nonuniform bandwidth allocation should be included in the final optimized design configuration.

3.5.3 Alternate Configuration: Modified Communications Availability

The baseline system performance for trunking systems assumes 99.9% communications availability. The impact of increasing the rain margin by +7 dB in order to increase link availability to 99.99% is shown in Table 3.5-5. If the performance change is made only in the spacecraft segment, then TWT power amplifiers with 5 W rf power per channel are required. The spacecraft power is increased by 2200 W, and a larger perigee motor is required. This leads to a total system cost increase of about $86 million.

Table 3.5-5. Impact of Increased Link Availability

Modification	Network/Performance Impact	Change of Space Segment Only
Increase rain margin by +7 dB	Link availability increased to 99.99%	Requires TWT with rf power of 5 W/chan New perigee motor required Power increase of 2200 W Cost increase of ~ $86 million Or
		Change of Ground Segment Only
		Requires 24 m antenna diameter plus cryogenic receiver and increased power amplifier level Cost increases by ~ $50 million

If the change were made in the ground segment only, it would require 24 m diameter antennas (which may not be technically feasible), cryogenic receivers, and increased transmitter power levels. Combined terminal cost would exceed $50 million. A combination of changes to baseline spacecraft and terminal configurations may be optimum.

In a similar manner, Table 3.5-6 shows the impact of reducing communications availability to 99.5%. The reduction of rain margin by 2 dB would lead to reduced spacecraft costs of $2 million or reduced terminal costs of $3 million. In view of the large decrease in performance and small cost savings, it is not recommended that performance be reduced to the diversity terminal network.

Table 3.5-6. Impact of Reduced Communications Availability

Modification	Network/Performance Impact	Change of Space Segment Only
Reduce rain margin by -2 dB	Link availability reduced to 99.5%	Rf power per channel reduced to 0.7 W Power reduced by 270 W Spacecraft weight reduced by ~ 165 lb Cost reduced by ~ $2 million Or
		Change of Ground Segment Only
		Diameter of antenna may be reduced to 10 m 10 site savings of ~ $3 million

3.5.4 Alternate Configuration: Spacecraft Power Tradeoff

Certain basic trades are indicated to reduce overall system costs and approach more nearly the optimum total program costs. Holding the bit rate constant and increasing spacecraft rf power in combination with reducing earth terminal G/T has the effect on total system cost shown in Table 3.5-7.

Table 3.5-7. Increased Spacecraft Power Tradeoff

Modification: Increase spacecraft rf power to save on user terminal costs				
System Cost Impact	FDMA		TDMA	
	+3 dB	+6 dB	+3 dB	+6 dB
a. Increase terminal LNA temp by 3 dB	+$1M	+$10M	+$9M	+$15M
b. Decrease terminal diameter & increase transmitter power	-$9M	-$ 5M	-$3M	+$ 1M
c. Decrease terminal diameter 3 dB, increase LNA 3 dB, and increase transmitter power		+$ 4M		+$ 7M

By increasing spacecraft rf power by 3 dB and merely raising the earth terminal LNA temperature by 3 dB, an increase in total program cost is incurred for both FDMA and TDMA systems. The significant increase in the TDMA system cost is due primarily to the doubling of spacecraft dc power and the extra batteries and electronic weight required.

If, however, the terminal diameter is reduced 3 dB, transmitter power increased by 3 dB, and LNA temperature held constant, some reduction is generally seen for system costs. It is noted that an increase in spacecraft rf power of +6 dB provides diminishing returns.

By decreasing terminal diameter by -3 dB, increasing LNA temperature by 3 dB, increasing transmitted power by +3 dB, and increasing spacecraft power by +6 dB, nothing is accomplished in reducing system costs. This is primarily due to a significant increase in spacecraft costs.

For the FDMA system, a trade was investigated looking to reduce the weight and complexity of the spacecraft subsystems. In this case, the spacecraft output modulation was examined to see if an FDM or TDM approach would reduce costs. The results of this trade are shown in Table 3.5-8 using the maximum reduction situation from the basic trade, namely line *b* in Table 3.5-7 with a +3 dB increase in spacecraft rf power. As can be seen, a significant reduction in power costs can be achieved for both the baseline and +3 dB increase in spacecraft rf power costs. The TDM alternative showed some decrease in system costs but not nearly as much as the FDM alternative.

Table 3.5-8. Spacecraft Power Tradeoff for Several Modulation Techniques

Modification: Increase S/C power and reduce earth terminal diameter		
System Cost Impact	**Baseline Spacecraft RF Power**	**+3 dB Spacecraft Power**
FDMA/FDMA (solid state)	Ref	-$ 9M
FDMA/FDM (TWTA)	-$2[illegible]M	-$23M

The basic conclusions drawn from these trades are:

- Reduction of the 12 m terminal antenna to 8.5 m not only saves costs but reduces installation problems and problems associated with wind loads and pointing.
- The FDM approach for the spacecraft output modulation significantly reduces spacecraft costs with attendant problems associated with multicarriers in a power amplifier.
- Further increases in spacecraft rf power beyond +3 dB reaches a diminishing return to scale primarily due to the earth terminal transmitter costs required to offset antenna diameter reduction. It is noted that in all cases, the systems are uplink limited.
- It is therefore concluded that a spacecraft FDMA/FDM configuration with approximately 10 W TWTA power amplifier is a sound alternative for the FDMA system, along with reduction in the earth terminal size and +3 dB increase in earth terminal power amplifier output.
- Although in all trunking system trades, TDMA configurations showed lower total program costs, the nonprogram TDMA development costs may well offset any program cost advantage for TDMA.

FDMA systems which require the power amplifier (ground or satellite) to amplify more than one carrier simultaneously suffer from generation of intermodulation which can degrade performance. Techniques for linearizing the TWTA HPA have been described (Bakken, 1974) but appear complex and costly. Frequency plans exist for placing the carriers to avoid the largest IM products. However, these schemes require excessive bandwidth. The most likely alternative is to back off the operating pointing of the HPA to the point where IM products are no longer objectionable. FACC has results from both experimental test (Chethik, 1976) and computer simulation (Lamin, 1975) which provide the relationship between back-off and IM levels.

Figure 3.5-3 from Chethik (1876) shows how the carrier-to-IM ratio varies as a function of backoff. Also shown is the tradeoff between increasing carrier-to-IM versus decreasing carrier-to-noise ratio as a function of the TWTA backoff. An optimum backoff exists, depending on the total carrier-to-noise-plus-IM ratio required (including uplink signal-to-noise ratio).

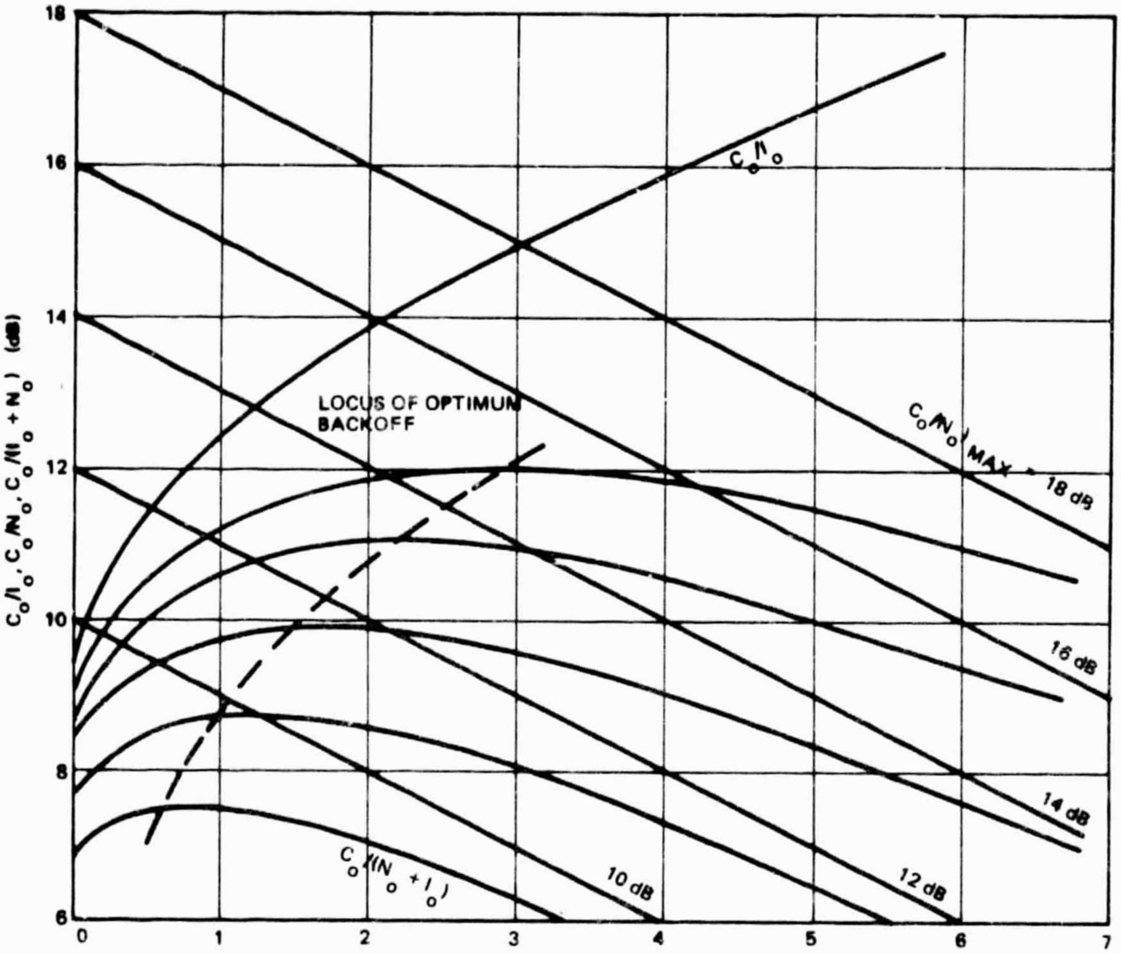


Figure 3.5-3. Intermodulation versus Transponder Backoff

The amount of TWTA backoff required is also a function of the type of modulation used. Thus an 8 PSK signal is more susceptible to IM than PSK or QPSK modulation and requires increased backoff. Backoff operation may be desirable even with only one carrier per TWTA if uplink is severely band-limited and TWTA AM/AM and AM/PM nonlinearities are significant. [Ref: Cuccia and Davies, 1976 and Lamin, 1977 for QPSK.]

3.5.5 Alternate Configuration: Elimination of Diversity Terminal

The impact of deleting the diversity terminal at trunking sites is presented in Table 3.5-9. In Case A the communications availability is maintained at 99.9%. The increased spacecraft power coupled with a 17 m single terminal with higher powered transmitters would add $37 million to overall system costs for a 10-site network. This would be offset by a $32 million savings through elimination of the diversity terminal. Additional development costs would also be incurred for the higher performance parameter single terminal configurations. A spacecraft configuration yielding 3.8 kW of array power is illustrated in Figure 3.5-4. An rf power of 5 W per channel may be obtained as compared with 1 W per channel for the baseline design.

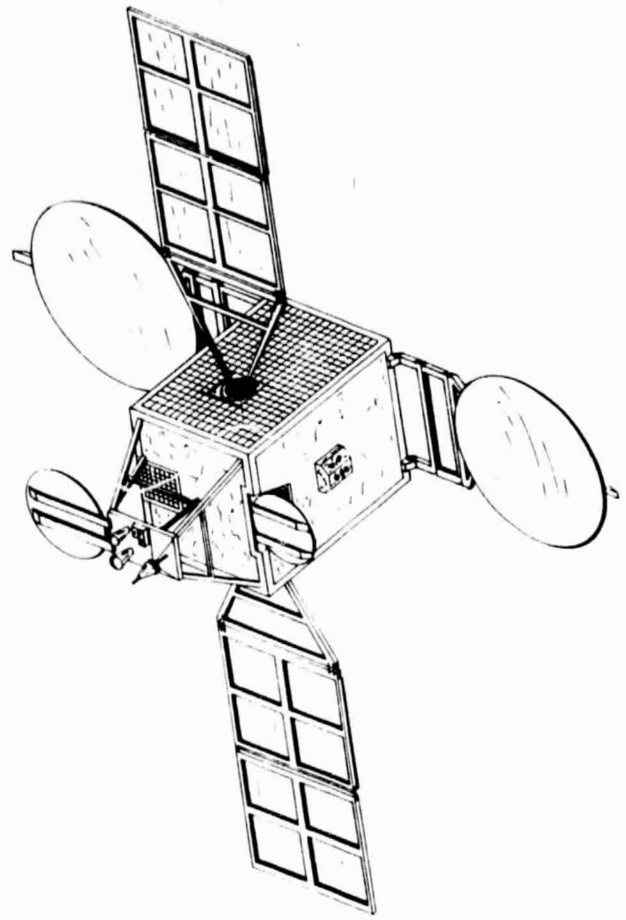
Table 3.5-9. Impact of Deleting Trunking Diversity Terminal

Modification: For 10-beam system and fixed-system capacity
a. Delete diversity terminal and maintain 99.9% availability.
b. Delete diversity terminal and reduce availability to 99.5%.

System Cost Impact	Case A 99.9%	Case B 99.5%
Δ S/C cost	+$21M	+$21M
Δ terminal cost	+ 16M	+ 11M
Eliminate 2nd terminal	- 32M	- 32M
Net cost impact	+$ 5M	0
Development risk	high	

Conclusions:
- Use of diversity terminal is cost effective for high communications availability (99.5%)
- High development risk for single terminal implementation (17 m antenna, cryo paramp, 1 kW/chan transmitter on ground)

If the diversity terminal were deleted, and the communications availability were allowed to decrease to 99.5%, then the savings in deleting the diversity terminal would equal the extra costs of the balance of the satcom system.



ON-ORBIT WEIGHT	2530 lb
LENGTH	21 ft
MAXIMUM ARRAY POWER	3.8 kW
RF POWER	5 W/CHAN
ANTENNA	10 BEAMS, 0.3°
PERIGEE MOTOR	SSUS-A UPGRADED

Figure 3.5-4. High Power Spacecraft for Trunking System

3.5.6 Alternate Configuration: Other Modulation Techniques

The baseline trunking system utilizes an FDMA modulation technique to access the spacecraft, and the 90 output channels are separately amplified in solid state 1 W amplifiers.

As shown in Table 3.5-10, if the FDMA uplinks are combined and a single 30 W TWT is used to amplify all the channels within a given downlink beam, then the spacecraft costs are reduced $22 million relative to baseline and the terminal costs are reduced $2 million relative to baseline. This saving may be offset, however, because the relative reliability of a 30 W TWT may be less than that of a 1 W solid state amplifier in achieving 10-year on-orbit life.

Table 3.5-10. Tradeoff for Alternate Modulation Techniques

Modification: Examine costs of various S/C modulation techniques			
System Cost Impact	**FDMA/FDMA**	**FDMA/FDM**	**FDMA/TDM**
Spacecraft rf power	90 X 1 W (S/S)	10 X 30 W (TWT)	10 X 10 W (TWT)
Spacecraft segment costs	$265M	$243M	$271M
Δ terminal costs	Ref	-$2M	-$4M

Conclusions:

- Use of FDMA/FDM saves $24M relative to baseline for 10-site network but uses TWT
- FDMA/TDM is more expensive and requires spacecraft switching; however, flexibility tc allocate capacity is greater

The FDMA uplinks may also be demodulated and all nine channels associated with a given downlink combined in a TDM format. This composite data stream would modulate a 10 W TWT (operated at saturation). The costs of processing to baseband and combining would increase spacecraft costs by $6 million relative to baseline; however, earth terminal costs are expected to be reduced by $4 million.

SECTION 4
DIRECT-TO-USER CONCEPTS

The direct-to-user (DTU) satellite communications system at 18/30 GHz is designed to accommodate a large number of user earth terminals (1000 to 10,000), which may be located anywhere within the continental United States (CONUS) excluding Alaska. The main feature of this type of configuration is that the user terrestrial network distribution costs are lower than trunking systems because of the larger number and greater geographic distribution of terminals. For DTU systems the total cost of the earth terminals generally exceeds that of the satellite segment and hence it becomes important to optimize the performance/cost relationship for unit terminals.

The approach used to document DTU concepts is (1) define overall requirements and coverage tradeoffs, (2) define a baseline system configuration using TDMA in detail, (3) define a summary approach using FDMA, and (4) examine other tradeoff alternatives. System costs and performance will be used as measures of relative desirability.

It is not to be interpreted that the baseline configuration is an optimized design; rather it is a viable total system concept that may be used to encompass all related system parameters in a unified framework that serves as a reference for evaluating the relative desirability of alternatives.

A large number of technical, economic, political, and user demand factors will influence future DTU system configurations at 18/30 GHz. These factors include the communications demand growth as a function of quality and circuit availability, scenarios for determining which companies will control or share control of the satellite network, desirability of large multifrequency band satellites versus smaller satellites operating at a signal band, desirability of uniform performance within CONUS independent of nonuniform demand, etc. Until the associated requirements for the satellite communications link are fully modeled, it is impossible to determine optimum configurations.

Subsection 4.1

DTU Requirements/Overview

The communications requirements for direct-to-user satcom operation are not firm at this time. To a certain degree the services demand requirements may be determined by the performance and cost of viable system concepts.

A baseline set of requirements was selected to provide a starting point for the configuration concept analysis. Subsequent analysis shows the impact of variances to the baseline. The range of configurations and performance parameters for DTU operation are shown in Figure 4.1-1. The delineated path within the matrix shows the baseline concept configuration. Selection criteria were established as follows:

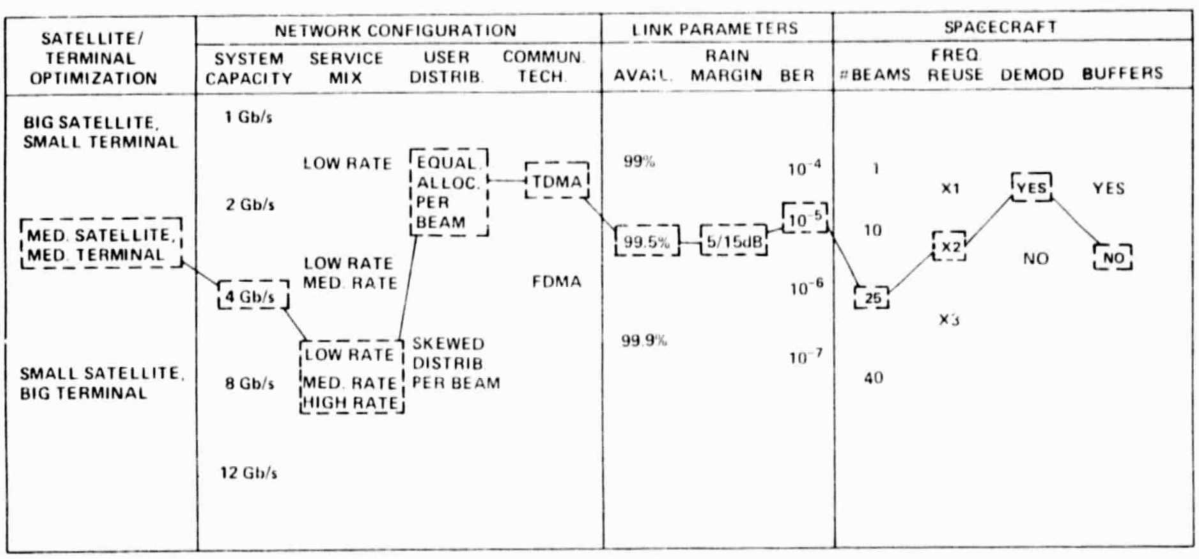


Figure 4.1-1. System Configuration Options

Satellite/Terminal Optimization

It is possible to operate direct-to-user systems with a very large spacecraft 10-20 kW of power, a medium spacecraft of about 4 kW of power, or a small spacecraft of less than 1 kW. The larger the spacecraft the smaller the demands upon the earth terminals. A medium spacecraft and a medium terminal were selected for the baseline because the critical path to the spacecraft is the uplink at 30 GHz and high spacecraft power does not help. A larger spacecraft is examined subsequently as an alternative. Because of the large number of earth terminals (1000 to 10,000) a small satellite does not present a viable alternative. Other selection criteria are determined by the STS launch vehicle characteristics. In general the share of launch costs are determined by spacecraft and associated perigee motor length rather than weight. Because the overall length is relatively constant for a wide range of spacecraft

power levels, the launch vehicle cost benefits associated with small spacecraft are minimal.

Network Configuration

The system capacity should be matched to user demand. The unit spacecraft throughput data rate can be established over a broad range of 1 Gb/s up to 12 Gb/s or more. A capacity of about 3.5 Gb/s was selected for the baseline, which evolved from information capacities of 150 Mb/s in each of the 25 beams. The planning for commercial carriers network implementation is also a factor. If each of several common carrier companies were to operate an 18/30 GHz DTU spacecraft at the same time, the unit capacity per spacecraft would become lower to meet an overall market demand for telecommunications services.

The service mix can range from low rate data at 64 kb/s (compatible with a digitized voice channel), through medium rate data at 1.5 Mb/s, to high rate data at 6.3 Mb/s. It is also possible to operate at rates up to 40 Mb/s; however the percent of capacity per beam available to other services would be considerably diminished. The baseline assumes accomodation of three types of service with about 50% of capacity allocated to low rate, 25% to medium rate, and 25% to high rate.

It is assumed that, for the baseline, all of the coverage beams are equal in size (about 1° half power beamwidth) and that the EIRP and G/T presented to any point within CONUS are equal. A uniform distribution of 1000 earth terminals (ie, 40 per beam) is also assumed; however, it is recognized that any optimized system configuration should match the real user distribution as much as possible. The other variable is the percent of traffic from given geographic areas which may be carried by alternate methods such as trunking at 18/30 GHz, other satcom transmission frequencies such as C-band and K_U-band, or via terrestrial networks.

The selection of communications technique impacts upon the flexibility for network implementation. A TDMA system is assumed for the baseline; however, an FDMA system is also examined as a viable alternative.

Link Parameters

Significant signal transmission attenuation is incurrred at the 18/30 GHz bands during heavy rainfall. Link margins may increase in order to minimize the outage during heavy rain, but system costs rise rapidly. The baseline DTU design provides 99.5% communications availablility (ie, 44 hours of outage per year) to single earth terminals (ie, no site diversity) through use of 5 dB rain margins at 18 GHz and 15 dB at 30 GHz. A communications bit error rate (BER) of 10^5 is assumed. Computer-to-computer data transfer at 10^7 to 10^9 BER can be achieved by trading off bandwidth capacity for error correcting coding.

It would be desirable to improve the communications availability to 99.9% (ie, 9 hours of outage per year). The link margins, however, would have to meet this performance level. The high levels of rainfall occur for short periods of time (15-30 minutes) in the late afternoon. Scheduling around the expected outage periods may improve customer acceptance.

Spacecraft Configuration

CONUS coverage can be obtained with a single spacecraft antenna beam; however, the

effective link gain is very small. A large number of beams (40 to 100) can be employed to improve the link gain, but the associated narrow beamwidths become much more difficult to point accurately and the interbeam interconnect within the spacecraft becomes very complex. A value or 25 equal beams of about 1° halfpower beamwidth is a compromise choice for the baseline DTU configuration.

It is possible to provide 3.5 Gb/s throughput capacity by a single use of the 2.5 GHz bandwidth available at K_A-band by using QPSK modulation. Because an approach using dual antennas per frequency was selected to minimize feed location problems it is feasible to use polarization diversity coupled with frequency diversity. This simplifies the filtering requirements.

The baseline spacecraft has a transponder configuration that demodulates each of the TDMA uplinks to a baseband data rate of 150 mb/s. This improves the overall signal-to-noise ratio performance and eliminates the need for a moderately complex frequency synthesizer in the spacecraft.

No signal processing, associated buffer storage, or special routing are required for the baseline design. These techniques do offer improvements in overall communications efficiency, but long-term spacecraft reliability is compromised and higher data rates are expected to be needed during implementation of the first generation system.

Subsection 4.2

Baseline TDMA Direct-to-User System

This subsection defines a baseline configuration using time division multiple access (TDMA) to meet expected requirements. The path shown in Figure 4.1-1 shows the parametric decisions for this approach, and the general concept of the baseline design is summarized in Figure 4.2-1.

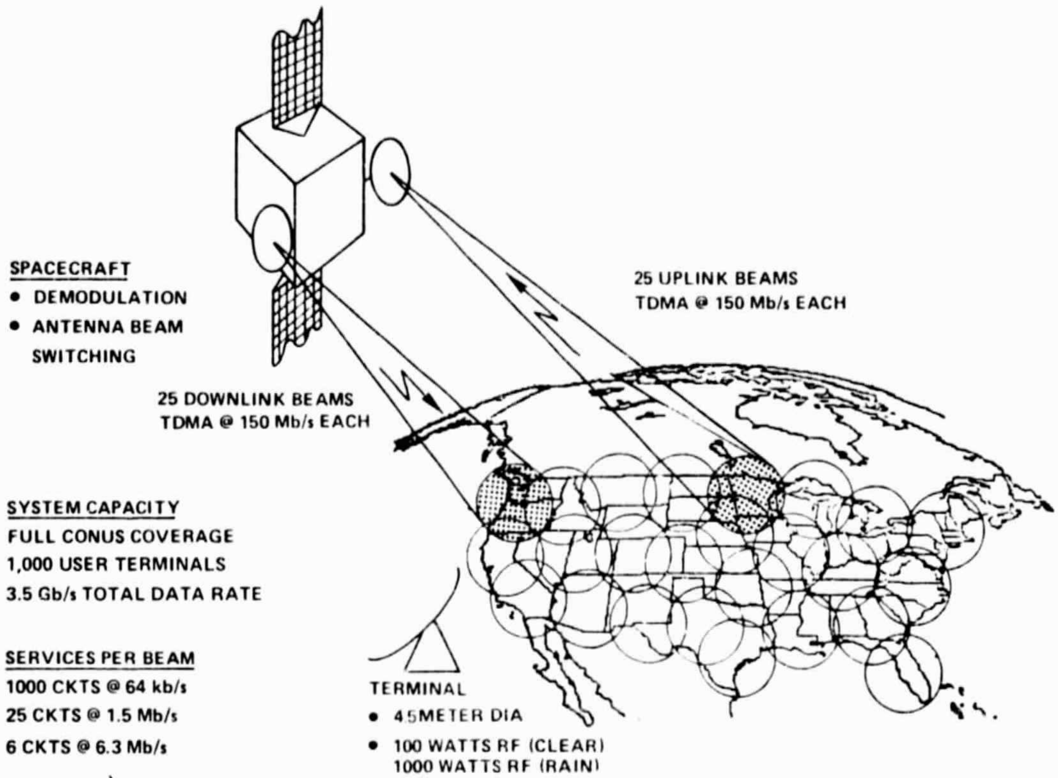


Figure 4.2-1. Direct-to-User at 18/30 GHz

4.2.1 System Configuration

The baseline system configuration is designed for direct-to-user (DTU) application among 1000 earth terminals located within CONUS. A nominal 140 Mb/s data rate in a TDMA mode is provided within each of 25 antenna beams. Demodulation, destination switching, and remodulation to TDMA format for downlink are achieved in the spacecraft. A single use of the full 2.5 GHz bandwidth allocated to satellite telecommunications at 18/30 GHz transmission frequency is required. Frequency reuse may be employed if greater system capacity is needed. Some bandwidth is reserved for beacon and TT&C operation as shown on the frequency plan of Figure 4.2-2. QPSK modulation is utilized to provide a 99.5% propagation reliability at a bit error rate of 10^{-5} to 95% of all user terminal locations.

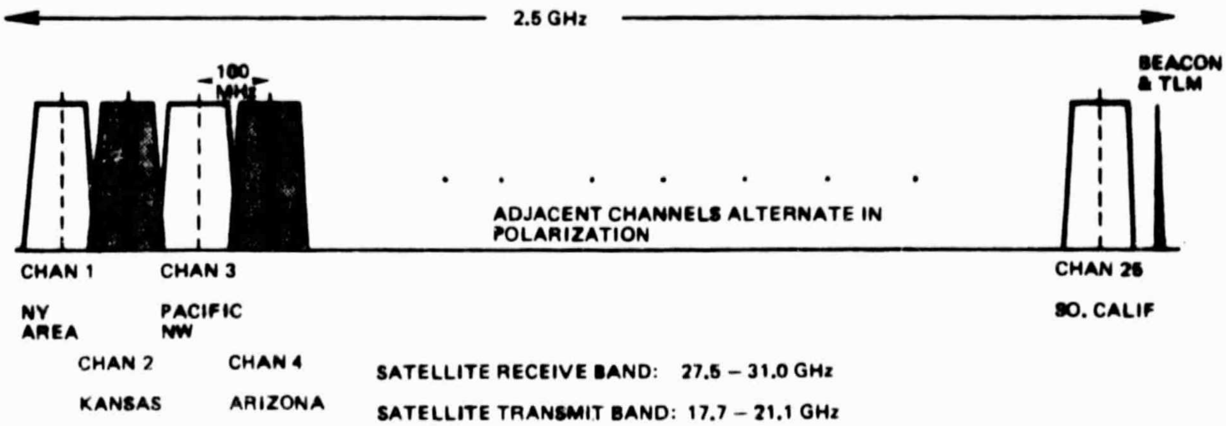


Figure 4.2-2. Frequency Plan for DTU System with TDMA

The satellite is shuttle launched. It has an on-orbit weight of 2650 lb and provides about 4.2 kW of solar power at beginning of life (BOL). The rf power per beam is 25 W and separate TWT amplifiers per beam are proposed. The satellite design lifetime is 10 years. A four-satellite program is planned: a qualification model that is later refurbished to flight level, two satellites for initial launch into synchronous orbit, and one spare satellite.

The earth terminal antennas are 4.5 meters in diameter, and no diversity terminal is provided; however, informal cooperation among users within a beam could be used to permit key data to be received with high reliability during heavy rainfall periods. The transmitter power per channel is 100 W in the normal mode and increases in steps up to 1000 W during rainstorms. Details on general system specifications are given in Tables 4.2-1 through 4.2-3.

Table 4.2-1. Satcom System Parameters - System and Communications

System

Direct-to-user system among 1000 terminals
Complete CONUS coverage
25 equal coverage antenna beams of 1° HPBW
Full system capacity of 3.5 Gb/s
TDMA modulation on uplink and downlink
Demodulation/remodulation and antenna beam switching in spacecraft
Satellite positioned at 100° west longitude
Single use of 2.5 GHz transmission band with 25 channels of 100 MHz each
No geographic diversity of earth terminals required

Communications

QPSK modulation at 10^{-5} BER
14 Mb/s data rate (15 Mb/s burst rate) within 100 MHz channel
System link margin of +3 dB minimum
99.5% propagation reliability for 95% of site locations
Use of 5 dB downlink rain margin and 15 dB uplink rain margin
Polarization diversity

Table 4.2-2. Satcom System Parameters - Satellite

Launch vehicle	Shuttle launch in 1985 – 1990 period
Perigee motor	SSUS-A (upgraded)
Number of Satellites	Refurbished qual model and three flight models Two downlink antennas of 3.8 ft diameter Two uplink antennas of 2.3 ft diameter Beam isolation of 25 dB minimum
Antenna pointing	To within ± 0.1° including alignment
Communications	Single TWTA power amplifier per beam (25) plus spares (25) RF power of 25 W per beam
TT&C	Use of K_A band for beacon and TT&C link
Eclipse operation	Battery capacity for 100% operation through maximum eclipse
Spacecraft mass	2650 lb on orbit
Spacecraft power	4200 W solar at BOL
Design lifetime	70% probability of achieving 10 year lifetime per spacecraft

Table 4.2-3. Satcom System Parameters - Earth Terminals

Network	1000 terminals located within CONUS
Diversity	Optional for higher availability
Antenna diameter	4.5 m
Transmitter power	100 W in clear mode, 1000 W in rainstorms
Receiver noise	Paramp receiver with 230 K noise temperature
Modems	Demodulate to baseband of 140 Mb/s Modular modem implementation to accommodate required data rates

DTU Network Configuration

The distribution of user earth terminals for 18/30 GHz satellite communications has not been established. The baseline design assumes an equal distibution of users for each coverage beam; however, techniques to accommodate a skewed distribution of users is examined under alternative configurations.

The baseline assumes that CONUS is covered with 25 overlapping antenna beams from the spacecraft position at 100° W longitude. One pattern for equal sized 1° half-power beamwidths is shown in Figure 4.2-3. One estimate of 10,000 user terminal distribution, assuming it to be proportional to the current traffic demands of 275 standard metropolitan statistical areas (SMSAs), is given in Table 4.2-4. It is shown that beam 1, which covers eastern New York and the New England area, may have 24% of the total number of terminals, whereas the beams covering sparsely populated areas of the country (Colorado, Utah, Montana, etc) may have less than 1% of the total number. This relative communications capacity normalized to the lowest regions is shown in Figure 4.2-4. The areas of heaviest shading are expected to have the greatest demand (New York City, Chicago, and Los Angeles).

The real distribution of user terminals will probably be affected by many other variables including the percent of traffic from given geographic areas that can be carried by alternate methods such as trunking at 18/30 GHz, use of other satcom transmission frequencies such as C-band and K_U-band, and use of existing or planned terrestrial networks.

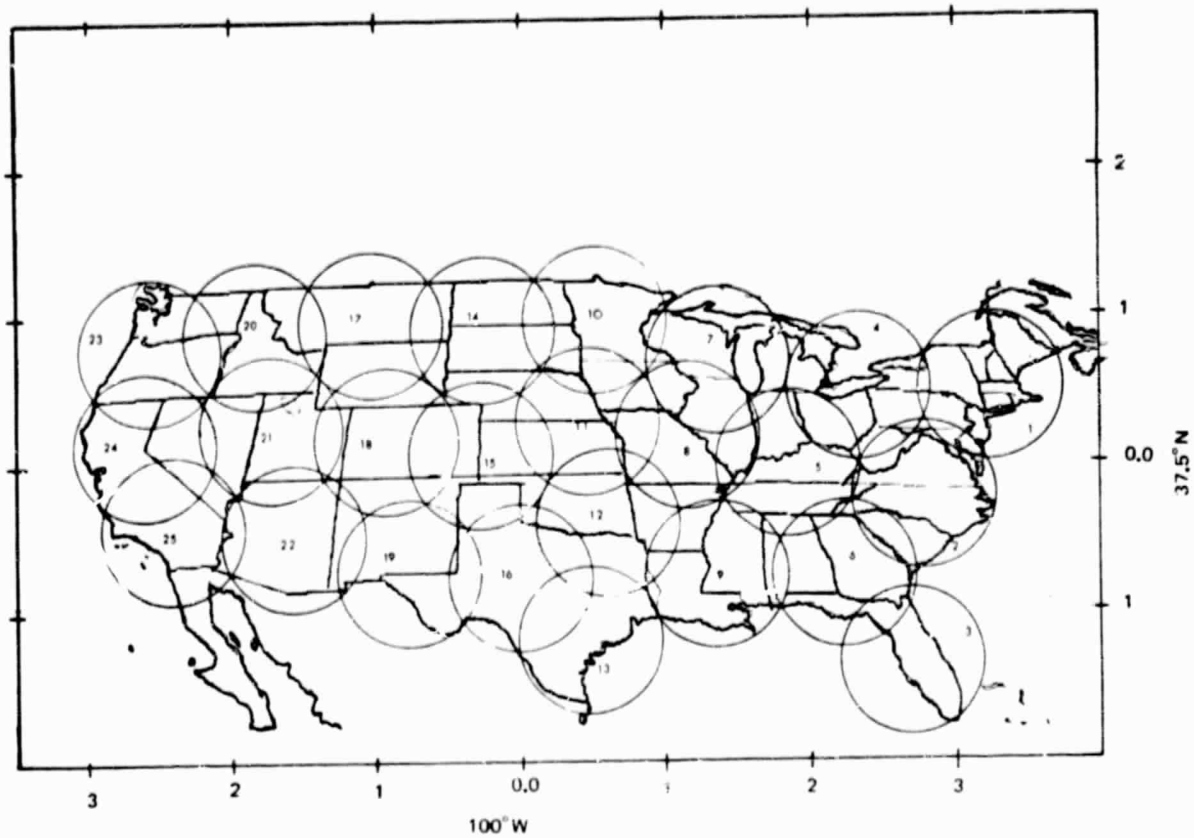


Figure 4.2-3. Antenna Coverage for 25-Beam DTU Systems

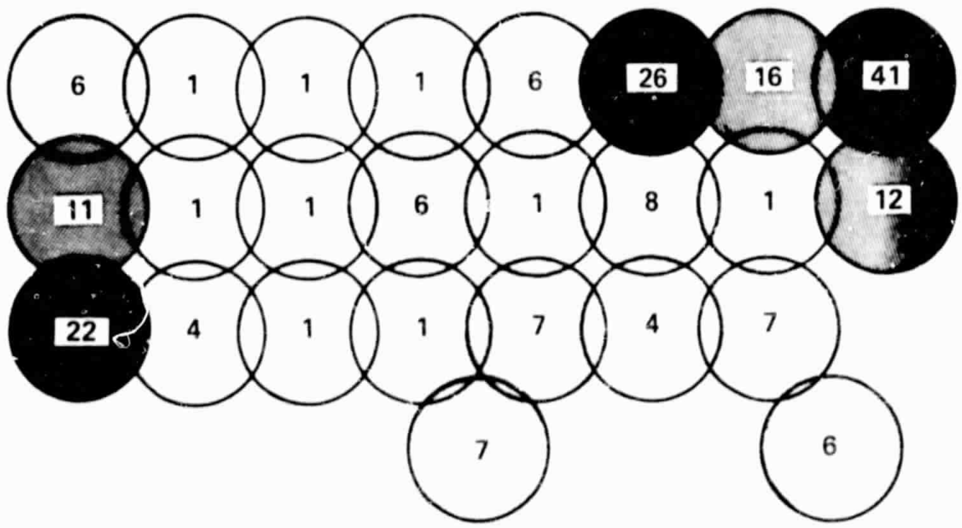


Figure 4.2-4. Relative Communications Capacity Requirements

Table 4.2-4. Terminal Distribution for 25-Beam System

Beam	Location	Number of Terminals	of Total
1	New York City & New England	2409	24.1
2	Mid Atlantic	904	9.0
3	Florida	430	4.3
4	Ohio, Pennsylvania	1382	13.8
5	Kentucky, Tennessee	816	8.2
6	Georgia, Alabama	323	3.2
7	Chicago, Wisconsin	746	7.5
8	Missouri	266	2.7
9	Louisiana, Mississippi	152	1.5
10	Minnesota	144	1.4
11	Kansas, Nebraska	68	0.7
12	Oklahoma, Dallas	372	3.7
13	Houston, Texas	233	2.3
14	Dakotas	7	0.1
15	Plains	100	1.0
16	West Texas	58	0.6
17	Montana	7	0.1
18	Colorado	20	0.2
19	New Mexico	58	0.6
20	Idaho	7	0.1
21	Utah	60	0.6
22	Arizona	119	1.2
23	Oregon, Washington	261	2.6
24	Northern California	468	4.7
25	Southern California	592	5.9
		10,000	100%

Based on ITT Distribution of 18 Oct 1978

Number of Antenna Beams

The satellite interconnect is considerably simplified if CONUS is covered with a single spacecraft antenna beam; however, the effective communications link gain is very small, about 25 dB at edge of coverage. If the number of beams is very large as shown in Figure 4.2-5, then the gain is high for improved link performance, but the problems of spacecraft implementation are increased due to the requirement for more accurate antenna alignment and pointing; more difficult feed layout, which requires multiple antenna reflectors; and a more complex interbeam interconnect matrix. The baseline of a 25 beam coverage represents a compromise choice that yields about 41 dB gain at edge of coverage. The half power beamwidth is about 1.0°.

ANTENNA BEAMWIDTH = 0.5 DEGREES
77 BEAMS REQUIRED FOR COMPLETE COVERAGE

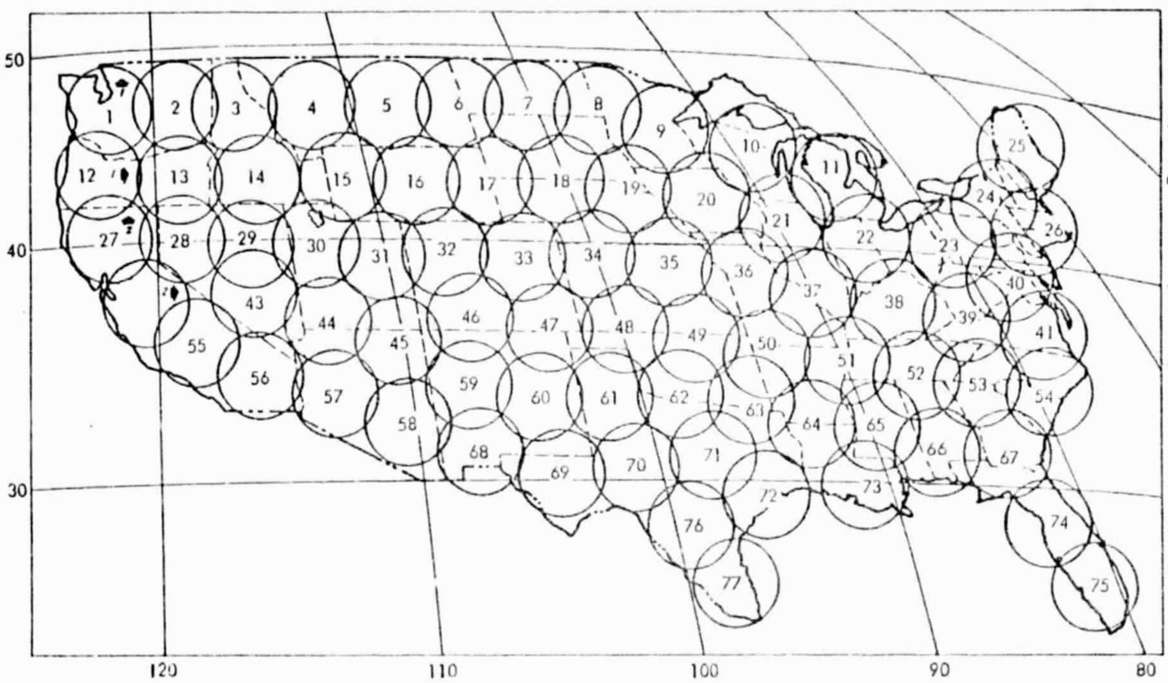


Figure 4.2-5. Narrow Beamwidth Full Coverage of CONUS

Several graphical and analytical techniques are available to determine the number of beams required to completely cover CONUS as a function of beamwidth. Figure 4.2-6 shows this tradeoff for the condition of beams overlapping at the -4 dB level from peak of beam. It is assumed that the spacecraft is at 100° W longitude and that the antenna aiming point is at mid-CONUS.

It is not practical to provide the contiguous beam coverage without employing separate frequencies (or orthogonal polarization) to maintain sufficient beam isolation. The number of beams using the same frequency is limited by the sidelobe structure of the antenna pattern. Since the peak amplitude of the sidelobes decrease with increased angular separation from the antenna axis, it is desired to limit frequency reuse to beams that are widely separated.

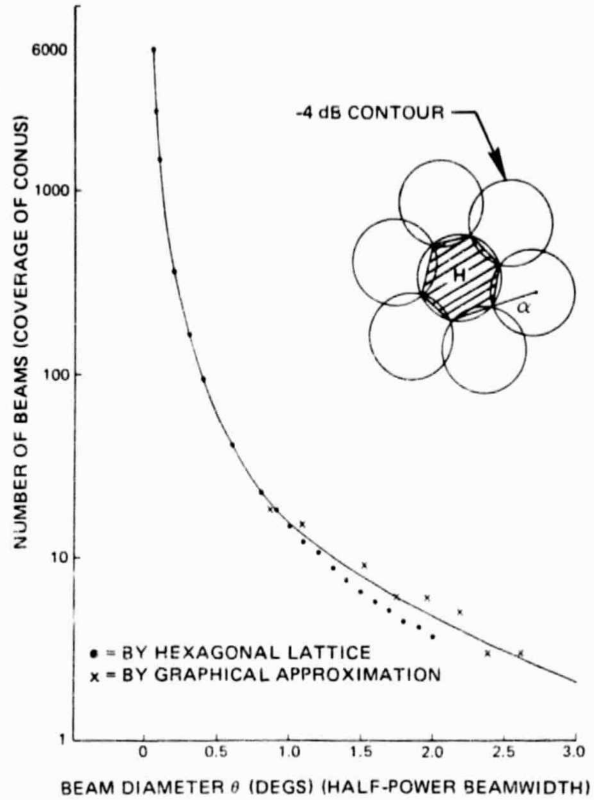


Figure 4.2-6. Number of Satellite Antenna Beams Required to Cover CONUS

Data Rates per Beam

The baseline design assumes three classes of data service. About 50% of system capacity is allocated to low rate data at 64 kb/s, 25% to medium rate data at 1.5 Mb/s, and 25% to wideband data at 6.3 Mb/s. The lower rate channels could be used for single channel digitized voice or digital data services. The higher rate channels are compatible with slow scan or limited motion teleconferencing in addition to other wideband data transfer requirements.

If the total throughput communications capacity of the spacecraft is to be 3.5 Gb/s, then the data rate for each of 25 equal beams is about 140 Mb/s. This leads to the channel allocation per beam for the assumed services allocation. Figure 4.2-7 shows the maximum instantaneous capacity per beam yields 6 channels of wideband data, 25 channels of medium data, and 1000 channels of low rate data. It is expected that the use of data packet preambles and guard time for TDMA operation would increase the communications burst rate to 150 Mb/s.

If each of the 25 beams carries an equal communications demand, then the peak number of low rate channels between each of the 625-beam pair (25 x 25) combinations is 40. As shown in Figure 4.2-8 the peak interbeam low rate data service for voice transmission may be increased by (1) communicating at increased burst rates, (2) varying the dwell time for interbeam interconnect to favor high demand regions (for example New York-Chicago), (3) restricting the classes of data service to low rate only, and (4) incorporating more efficient voice compression modems.

6 channels of wideband data at 6.3 Mb/s =	37.8 Mb/s	(27%)
25 channels of medium data at 1.544 Mb/s =	38.6	(27%)
1000 channels of low rate data at 64 kb/s =	64.0	(46%)
	140.4 Mb/s	

To permit guard band and preambles on data packets, the communications burst rate would be 150 Mb/s.

Figure 4.2-7. Data Rate per Antenna Beam

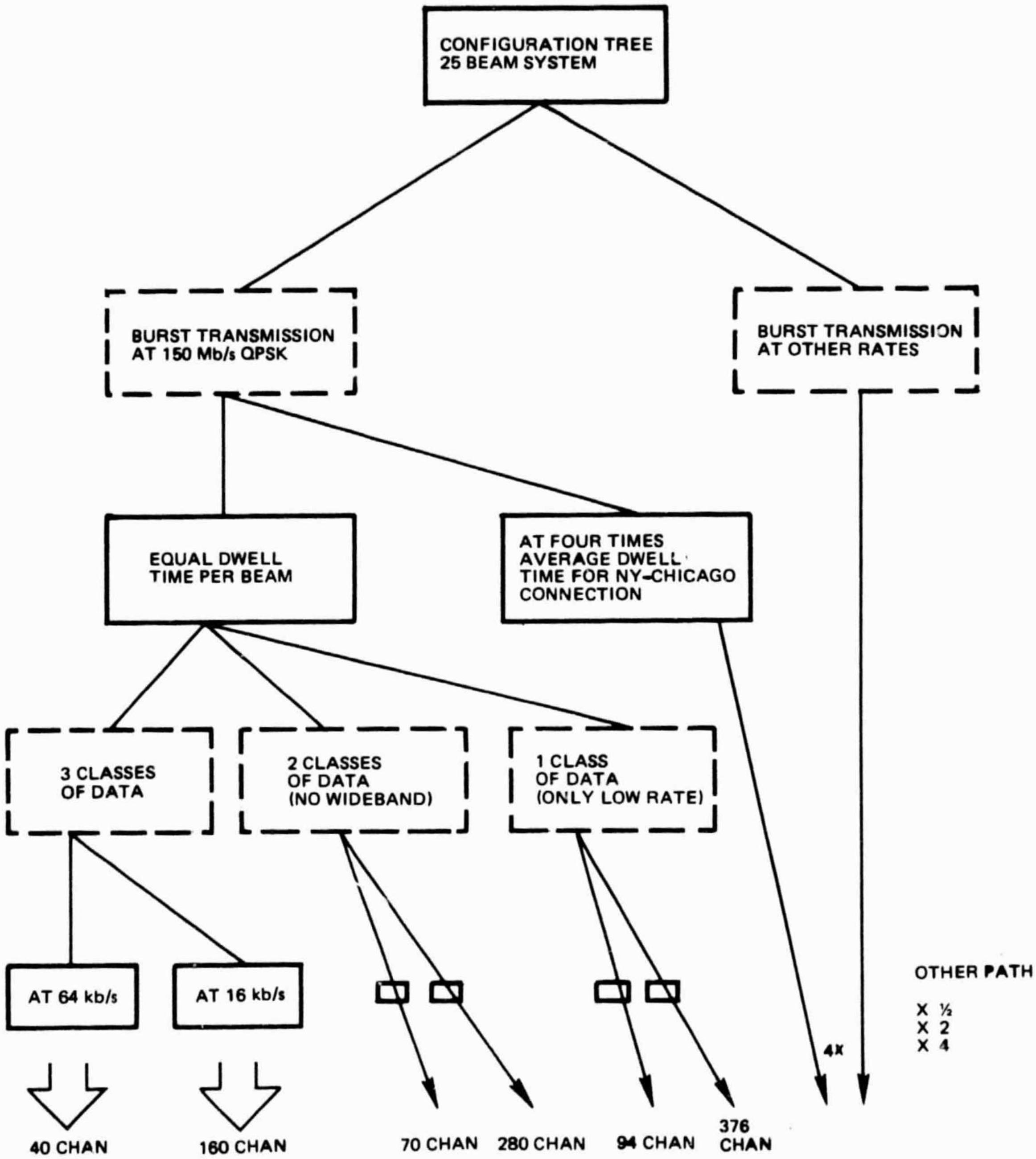


Figure 4.2-8. Interbeam Peak Low Rate Data Service

Terminal Utilization Tradeoff

If the system communications capacity is fixed (ie, 3.5 Gb/s) and the number of earth terminals per beam is increased, then the average time available to each terminal is reduced. Figure 4.2-9 shows the tradeoff of average capacity per terminal as a function of the number of user terminals per beam for several peak-to-average usage ratios.

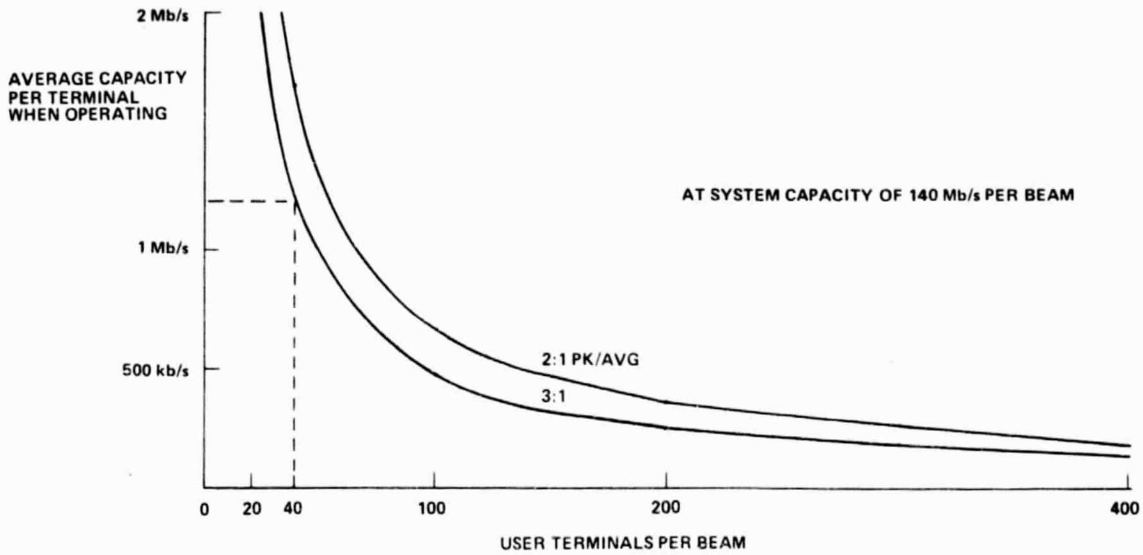


Figure 4.2-9. Capacity/Utilization Terminal Tradeoff

It is shown that for a system capacity of 140 Mb/s per beam and 40 user terminals per beam the average capacity per terminal when operating at a 3:1 peak-average ratio is about 1.2 Mb/s. This would translate to 8 hours per day at 1.2 Mb/s, 4 hours at 2.4 Mb/s, etc.

In order to promote the use of the system during the off-peak hours it may be desirable to offer a lower communications rate in a manner similar to that of current telephone call charges. Much of the bulk data transmission may be achieved with unattended operation at both transmit and receive terminals.

Frequency Reuse/Polarization Diversity

The baseline DTU system for 3.5 Gb/s system capacity may be implemented with single use of the available frequency spectrum at K^A band. Considerable expansion in data capacity may be achieved through frequency reuse by utilizing the spatial isolation of the relatively narrow 1° coverage beams.

A further degree of isolation or data rate expansion may be used for subsequent expansion by using polarization diversity. Unfortunately the relative isolation during heavy rainfall periods may be degraded to polariztion crosstalk ratios of about -20 dB.

Rain-induced depolarization causes a deterioration in system cross-polarization isolation, ie, a decrease in total available carrier-to-noise into the demodulator. The theory of rain-induced depolarization is based on the existence of oblate and spheroidal raindrops and their orientation with respect to the direction of propagation of the incident electromagnetic signals (assumed to be plane waves). The parameters of the theoretical model that attempt to describe this relative orientation are actually random variables. As such, they are not subject to evaluation with the same accuracy as are the parameters of the model of rain-caused attenuation. Consequently, verification of theory by experiment is not as complete as it is for rain-caused attenuation.

One simple plan for combining polarization diversity with frequency diversity is shown in Figure 4.2-10. The east and west coast regions have fewer beams per region and are assigned vertical polarization during heavy rainfall periods.

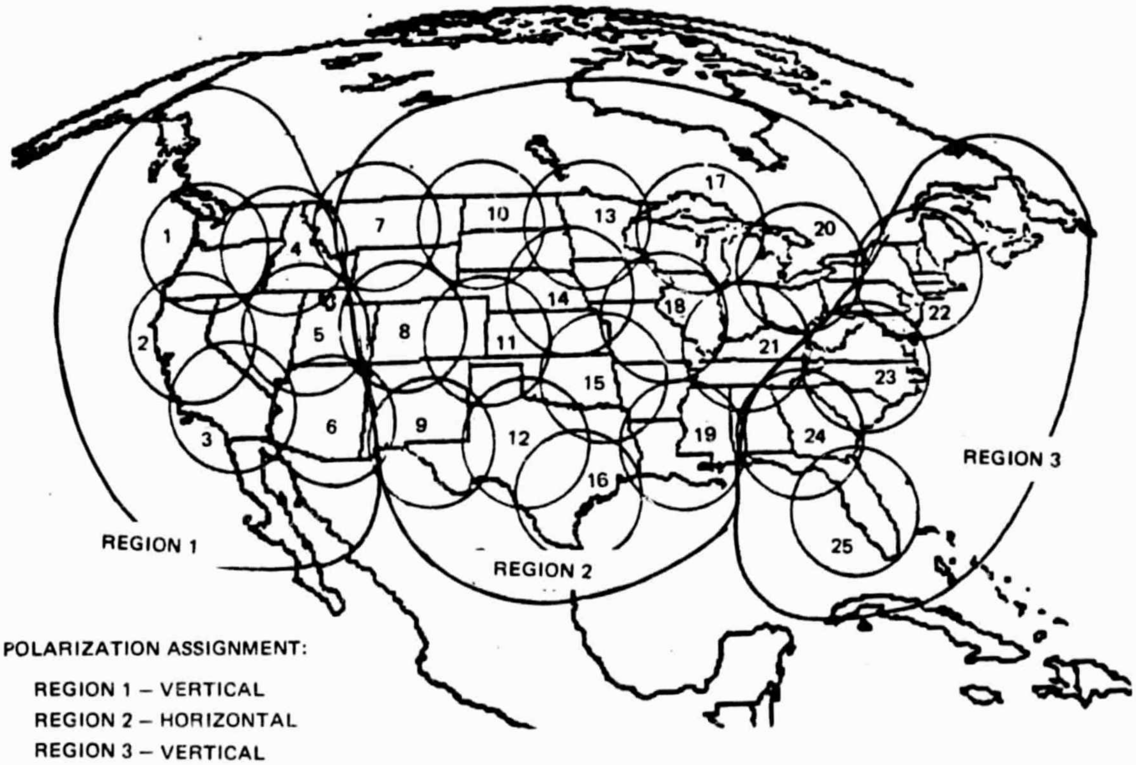


Figure 4.2-10. Polarization Diversity Plan for 3X Frequency Use

4.2.2 DTU Communications Links

The following paragraphs describe the baseline design configuration of the DTU communications link. The key aspects of TDMA frame formatting, link budget allocation, and rainfall effect upon single terminal users within CONUS are described.

4.2.2.1 DTU TDMA Frame Formats

One method for accommodating a large number of user terminals in a TDMA format is illustrated in Figure 4.2-11. The spacecraft transponder demodulates the uplink data stream from a particular beam coverage area, for example beam 4. The 140 Mb/s data rate is broken into intervals of time, which for this example are 1/750 of a second. For this period the uplink from beam 4 is connected to open downlink antenna by means of a baseband switch. About 186,000 bit of information are transmitted during a particular interconnect. As shown, about 84,000 bits are allocated for low data rate transmission at 64 kb/s, 50,000 bits are allocated to medium rate transmission at 1.5 Mb/s, and 52,000 bits are allocated to wideband data at 6.3 Mb/s. This provides 40 channels of low rate data between beam 4 and each of the 25 downlink beams, 1 channel of medium rate data to each downlink beam, and 1/4 channel of high rate data to each downlink beam. The 1/4 channel to each of 25 beams is not feasible, hence on a controlled basis beam 4 is permitted wideband communications to six selected downlink beams.

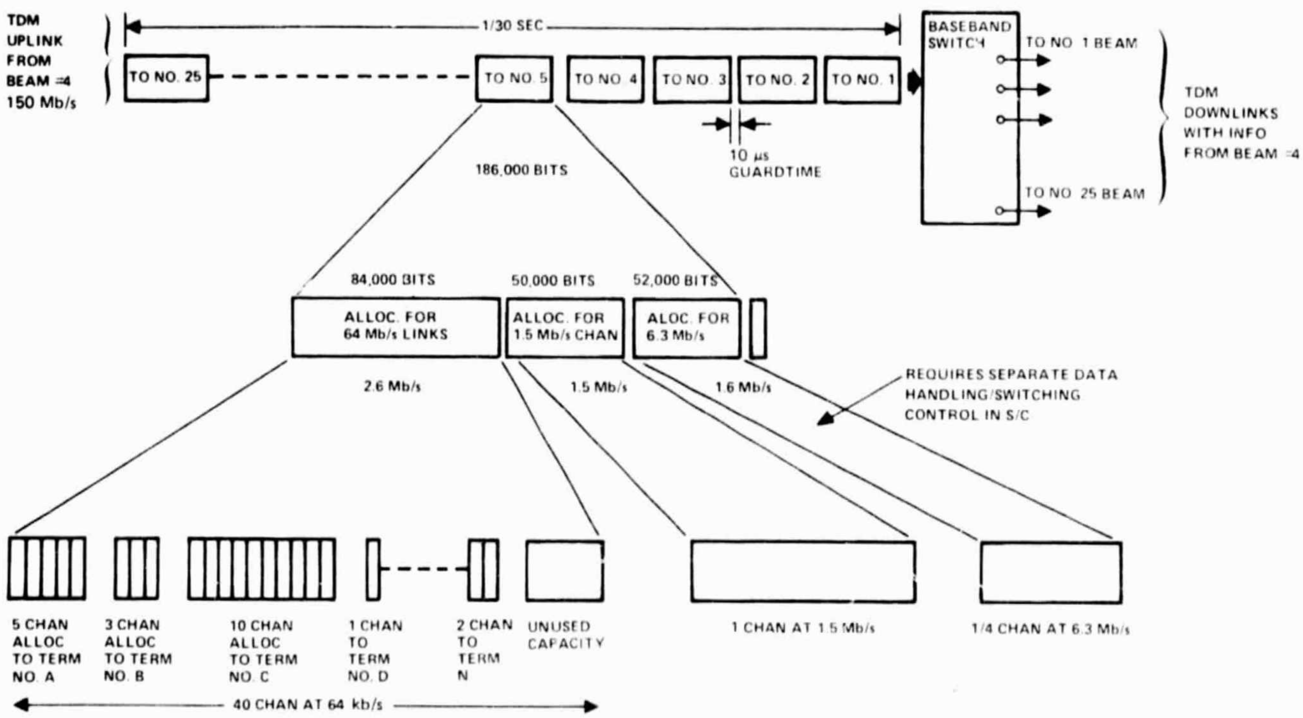


Figure 4.2-11. TDMA Frame Formats

The spacecraft baseband switch is operating at a rate of 750 antenna pair reconfigurations per second. A 10 μs guard time is established between blocks of area paired data in order to permit time for the switching and margin for system timing error. The technology limit on-time for a switch is of the order of 20 to 50 ns; hence the 10 μs guard band permits conservative techniques to be used. The guard penalty on system data capacity remains less then 1%.

The baseline frame format switches through all of the 25 beam area destinations within 1/30 of a second and then repeats the cycle. Thus, if a voice circuit is digitized to 64 kb/s, a block of about 2100 bits plus preamble may be sent 30 times per second from a terminal within beam 4 (for example) to a selected destination beam area. A modem buffer storage of about 2 kb is required for both transmit and receive in order to smooth data to real-time voice.

The channel assignment within the TDMA frame format may be achieved by preassigned time slots or by a controlled demand access or by a combination of methods.

The accommodation of the wideband 6.3 Mb/s data is established by using a special buffer storage and controlled switching matrix in the spacecraft. Any uplink beam may receive up to six wideband channels, and any downlink beam may receive up to six wideband channels. It is possible to have a selected uplink beam communicate a wideband signal to a multiple number of downlink beams simultaneously.

4.2.2.2 DTU Link Budget

The configuration of a satellite communications link for DTU application using TDMA is shown in Figure 4.2-12. A transmit terminal obtains a time slot (fixed assigned or demand access via orderwire to communications control center) for transmittal of a selected data rate to a selected terminal located within one of the 25 downlink coverage areas. During clear weather the composite blocks of data are transmitted within precisely controlled time intervals at a burst transmission rate of 150 Mb/s. The earth terminal transmitter operates at 100 W during clear weather; however, the rf output is step controlled up to a maximum rf power of 1000 W during heavy rain periods.

The satellite receives the signal within the 27.5 to 30 GHz transmission band, amplifies it, and demodulates it. A baseband switch connects the originating signal to a downlink circuit for 1/750 second (as part of a cycle interconnect pattern). The baseband signal is modulated, translated to a nominal 18 GHz downlink frequency, amplified with a 25 W rf TWTA, and directed to one of the 25 downlink antenna beams.

The receiving terminal monitors all transmissions on the downlink within a given coverage area and identifies the preamble data signifying those transmission bursts for the selected receiving terminal. Demodulation is accomplished in the appropriate data rate modem.

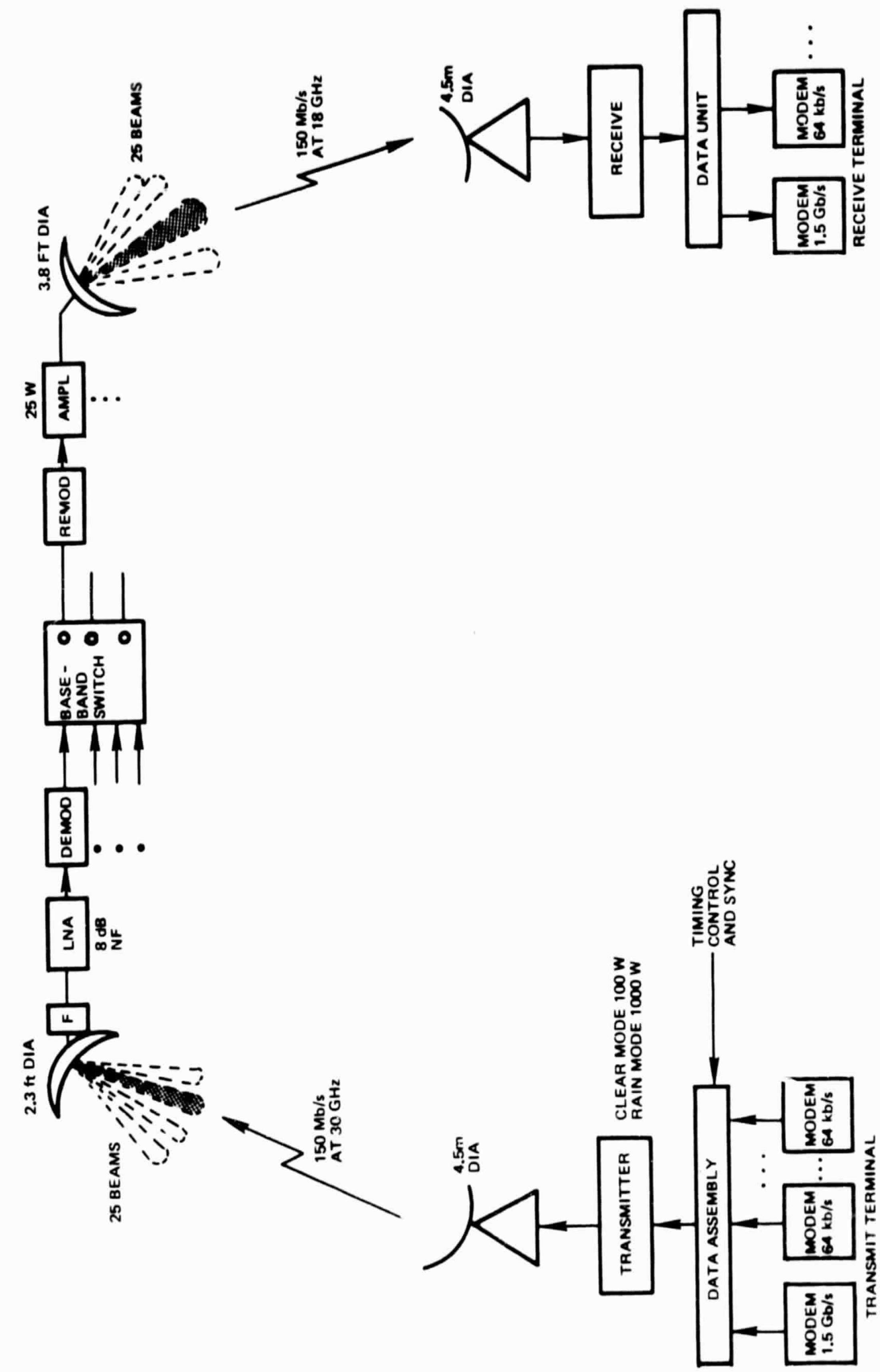


Figure 4.2-12. DTU Link Configuration

A summary link budget is given in Table 4.2-4 and additional details are provided in Tables 4.2-5 through 4.2-7. One of the key factors affecting link design is the amount of margin to accommodate rain attenuation. It is expected that 95% of all the terminal locations within CONUS would be able to have 10^{-5} bit error rate data quality 99.5% of the time if the uplink rain margin provided was 15 dB and the downlink margin was 5 dB. (Also see paragraph 4.2.2.3 for detail.)

These values apply to single antenna configurations. If dual earth terminal site diversity was provided the margins could be considerably reduced. Diversity interconnect is not economically viable because costs of the terminal sites would roughly double.

It is shown that for the normal condition of no rain (more than 98% of the time) an uplink margin of +3.7 dB and a downlink margin of +7.4 dB are obtained. This provides a data quality with bit error rate of 10^{-9} or better. It should also be noted that these margins are for the condition of a maximum antenna pointing error, a terminal located at the edge of a coverage area, and a 3 dB equipment degradation factor.

Table 4.2-4. Summary Link Budget for 150 Mb/s QPSK

Item	Case 1 No Rain	Case 2 Uplink Rain	Case 3 Downlink Rain
Uplink (30 GHz):			
Ground antenna (4.5 m dia)	+ 60.4 dB		
Transmitter power per channel	+ 20.0 dBW	+ 29.0	
Rain attenuation for 99.5% availability	0.0	- 15.0	
Satellite antenna gain (2.3 ft dia) at EOC	+ 41.2 dB		
	+ 98.4 dB-Hz	+ 92.4	+98.4
Uplink Net C/kT			
Downlink (18 GHz):			
Satellite antenna gain (3.8 ft dia) at EOC	+ 41.2		
Transmitter power/beam (25 W)	+ 14.0 dBW		
Rain attenuation for 99.5% availability	0.0 dB		- 5.0 dB
Ground antenna gain (4.5 m dia)	+ 57.0 dB		
Noise temperature	- 24.8 dB-K		-26.2
	+101.1 dB-Hz	+102.1	+95.7
Downlink Net C/kT			
Combined Link: @10^{-6} BER			
Uplink margin	+ 3.7 dB	- 2.3 dB	+ 3.7 dB
Downlink margin	+ 7.4 dB	+ 7.4 dB	+ 1.0 dB
Net link performance	$\approx 10^{-9}$ BER	$\approx 10^{-4}$ BER	$\approx 10^{-6}$ BER

Table 4.2-5. Detailed Link Budget for 150 Mb/s QPSK with Spacecraft Demodulation/Remodulation

	Case 1 No Rain	Case 2 Uplink Rain	Case 3 Downlink Rain
Uplink (30 GHz):			
Grd Ant Gain (4.5 meter dia) Peak	+ 60.4 dB		
Xmitter Power (100/1,000 W)	+ 20.0 dBW	+ 30.0	
Xmitter Line Losses	− 2.0 dB	− 3.0	
Pointing Loss	− 1.5 dB		
Propagation Path Loss (at 45° elev)	−213.5 dB		
Atmospheric Atten	− 1.1 dB		
Rain Atten for 99.5% Availability	0 dB	− 15.0	
Boltzmann Constant	+ 228.6 dBW/K-Hz		
Sat Ant Gain (2.3 ft dia) at EOC	+ 41.2 dB		
Receive Noise Temp (NF = 8 dB)	− 31.9 dB-K		
Feed and Line Loss	− 1.5 dB		
Pointing Loss	− 0.3 dB		
Uplink C/kT	+ 98.4 dB-Hz	+ 92.4	+ 98.4
Required C/kT for 10^{-5} BER	94.7	94.7	94.7
Net Uplink Margin	+ 3.7 dB	− 2.3 dB	+ 3.7 dB
Downlink (18 GHz):			
Sat Ant Gain (3.8 ft dia) at EOC	+ 41.2 dB		
Xmitter Power/Chan (25 W)	+ 14.0 dBW		
Xmitter Losses	− 1.5 dB		
Pointing Loss (at EOC)	− 0.3 dB		
Propagation Path Loss (at 45° elev)	−209.1 dB		
Atmospheric Atten	− 0.5 dB		
Rain Atten for 99.5% Reliability	0.0 dB		− 5.0
Boltzmann Constant	+ 228.6 dBW/K-Hz		
Grd Ant Gain (4.5 m dia) Peak	+ 57.0 dB		
Noise Temp (300/410 K)	− 24.8 dB-K		− 26.2
Receive Losses	− 1.5 dB		
Pointing Loss	− 1.0 dB		
Downlink C/kT	+ 102.1 dB-Hz	+ 102.1	+ 95.7
Required C/kT for 10^{-5} BER	94.7	94.7	94.7
	+ 7.4 dB	+ 7.4 dB	+ 1.0 dB
Net System Performance	≈ 10^{-9} BER	≈ 10^{-4} BER	≈ 10^{-6} BER

Ford Aerospace & Communications Corporation

Table 4.2-6. Details of DTU Link Calculation

Uplink Parameters

a. Ground Terminal

1. Ideal on-axis gain of a 4.5 m dish of 62.9 dB less aperture efficiency loss with 0.04 inch rms surface of 2.5 dB equals net on-axis gain of 60.4 dB.
2. Waveguide and diplexer losses of -2.0 dB for 100 W power amplifiers located at feed and 3.0 dB for 1000 W power amplifier located at base of antenna.
3. The power amplifier for normal mode of operation is assumed to be a 100 W uncooled parametric amplifier. During heavy rain periods a 1000 W parametric amplifier would be switched into operation.
4. The half-power beamwidth of the 4.5 m dish is 0.16° at 30 GHz. Antenna step-tracking is required, and it is estimated that the maximum pointing loss is -1.5 dB.
5. The net ground terminal EIRP at maximum pointing loss is therefore -76.9 dBW for clear sky conditions.
6. The EIRP increases to +85.9 dBW when using the high power transmitter.

b. Propagation Losses

1. The path loss associated with a 45° elevation angle to the satellite is -213.5 dB. If the satellite is located at 100° W longitude, then the elevation angles range from 32° (New York) to 55° (Houston). The extremes would change the path loss factor by ±0.2 dB.
2. The normal atmospheric attenuation during clear sky conditions is -1.1 dB for 10 grams of water per cubic meter.
3. An additional rain attenuation factor of 15 dB is included to assure 99.5% propagation reliability for 95% of the terminals located within CONUS. Diversity terminal operation is not required.

c. Satellite Receiving

1. The net gain of a 2.3 ft diameter spacecraft antenna is 41.2 dB at the edge of coverage of a 1.0° beam. The gain at the peak of the beam is approximately 3 dB higher.
2. The receiving antenna feed and line loss is -1.5 dB.
3. A spacecraft antenna pointing loss of -0.3 dB is obtained from a maximum ±0.1° error in pointing.

d. Net uplink C/KT in clear sky condition is +98.4 dB-Hz.

Downlink Parameters

a. Satellite

1. Satellite transmitting power of 25 W per beam is obtained by operating a TWTA at saturation.
2. The net gain of a 3.8 ft diameter spacecraft antenna is 41.2 dB at the edge of coverage of a 1.0° beam. The gain at the peak of the beam is approximately 3 dB higher.
3. The line loss from output of the power amplifier to selected antenna beam feed is -1.5 dB.
4. A spacecraft antenna pointing loss of -0.3 dB is obtained from an overall spacecraft alignment and attitude control error of ± 0.1°.

b. Propagation Losses

1. The path loss associated with a 45° elevation angle to a satellite at 100° W longitude is -209.1 dB. The path length factor will change by about ± 0.2 dB for the extremes of look angles to the satellite from terminal locations within CONUS.
2. A standard atmospheric attenuation factor of -0.5 dB is obtained during clear weather conditions.
3. An additional rain attenuation factor for a 99.5% capability at 18 GHz is about -5 dB. Diversity terminal operation is not required.

c. Ground Terminal

1. Ideal on-axis gain for 4.5 m reflector of +59.3 dB less feed and aperture efficiency loss (0.04 inch rms surface) of 2.3 dB equals net on-axis gain of +57.0 dB.
2. Waveguide and diplexer loss for LNA mounted at feed is estimated to be -1.5 dB.

Table 4.2-6. Details of DTU Link Calculation (Continued)

3. The half power beamwidth of the 4.5 m dish is 0.24° at 20 GHz. Antenna step-tracking is required, and it is estimated that the maximum pointing loss is -1.0 dB.
4. An uncooled paramp receiver of 230 K noise temperature and clear sky noise temperature of 70 K would result in a receiving system noise of 300 K or -24.8 dB/K during clear weather. The sky noise would increase to about 180 K for 5 dB rain attenuation; hence, the system noise increases to 410 K or -26.2 dB during 99.5% rain conditions.

d. The net downlink C/kT in clear sky condition is +102.1 dB.

Combined Link Parameters

a. For this system configuration it is assumed that the spacecraft demodulates the uplink signal to baseband, switches to appropriate antenna beam, and then remodulates on a 30 GHz carrier. Thus the uplink and downlink may be independently assessed for contribution to error.

b. Required system C/kT for 150 Mb/s at 10^{-5} BER when using QPSK is +94.7 dB-Hz. This factor includes a +3.0 dB margin for system and equipment degradation to theoretical values.

c. The worst case condition for system operation is the uplink during heavy rainfall, which shows a negative margin of -2.3 dB for 10^{-5} BER. This could be improved by increasing the diameter of the earth terminal antenna to 6.2 m, or using a 1800 W transmitter, or by using site diversity, or by accommodating a lesser percentage of terminals at the 99.5% availability, or by changing the overall availability requirement.

d. During clear sky conditions (> 99% of time) an overall bit error rate of about 10^{-9} is obtained.

Table 4.2-7. Receive Requirements

E_b/N_o theoretical for 10^{-5} BER	=	9.9 dB
Bit rate factor (for 150 Mb/s)	=	81.8 Hz
System and equipment degradation	=	3.0 dB
a. Bandwidth limiting causing intersymbol interference		
b. Nonlinearities and unbalance of power amplifiers		
c. Matched filter mismatch due to band limiting		
d. Carrier & sync loop jitter & bias		
Net required C/KT	=	94.7 dB-Hz

4.2.2.3 Rain Attenuation for DTU Link

The concept of DTU communications would be implemented with a single earth terminal located in close proximity to the user. The effects of rainfall attenuation become more pronounced than for trunking systems because geographic diversity of a second terminal is not employed. The detailed analysis of rainfall attenuation is discussed in subsection 2.3, whereas this paragraph highlights the impact on DTU application.

Terminal Location

The location of the earth terminal within CONUS has a major effect on communications availability. The general rainfall regions are shown in Figure 4.2-13. Table 4.2-8 lists the average rainfall expected in each region and also the percent of rain by thunderstorm. The worst case region climate is zone 5. This is the gulf area of southeast United States, where the average rainfall is 64 inches per year and 50% of the rain occurs by thunderstorm. A single site terminal rain margin of 7 dB is required at 18 GHz and 17 dB at 30 GHz in order to achieve 99.5% communications availability.

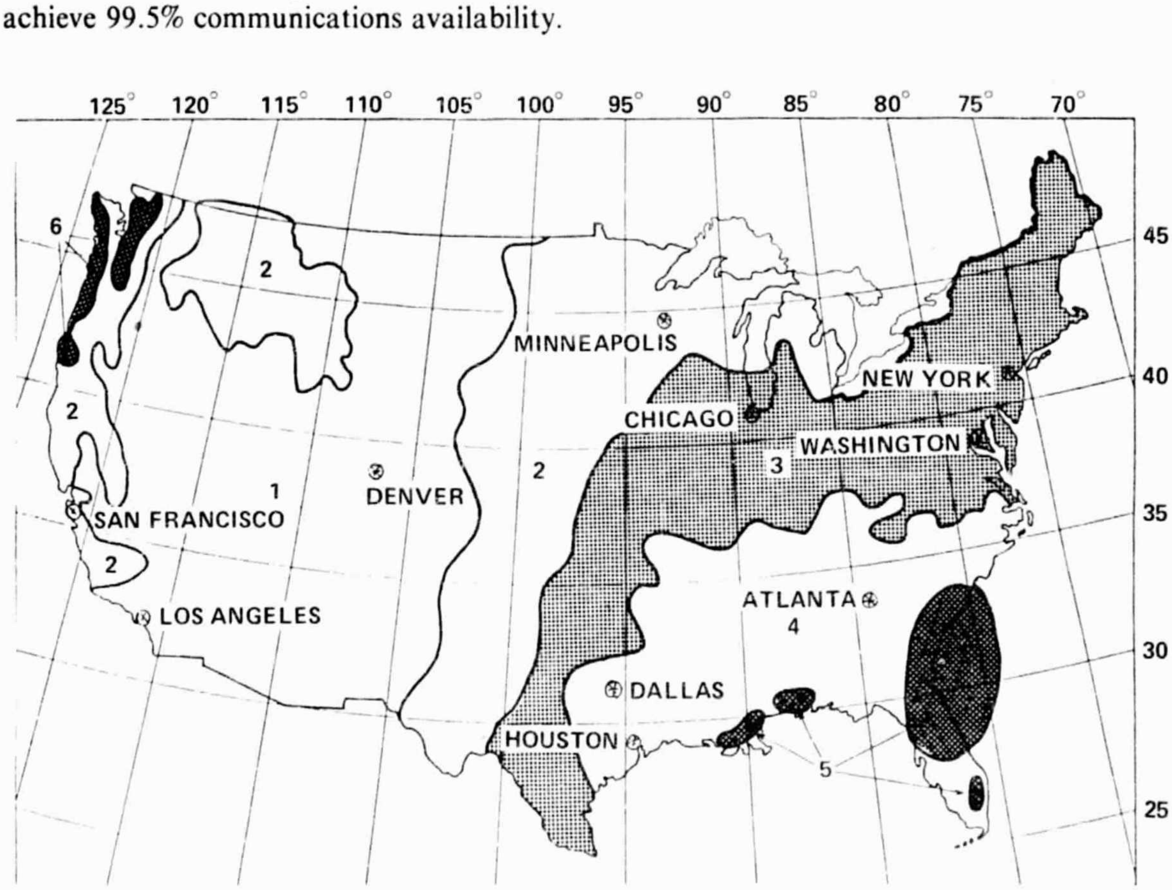


Figure 4.2-13. CONUS Climate Zones

Table 4.2-8. Rain Margin Requirements for 99.5% Reliability

Climate Zone	General Area	% of Population	Average Annual Rainfall	% Rain by Thundercloud	Single Site Rain Margin	
					18 GHz	30 GHz
1	Deserts	10%	10 in.	20%	2 dB	5 dB
2	Plains	21%	24 in.	20%	3 dB	8 dB
3	Midwest, coasts & northeast	47%	40 in.	25%	4 dB	11 dB
4	Southeast	16%	56 in.	40%	5 dB	14 dB
5	Gulf areas	4%	64 in.	50%	7 dB	17 dB
6	Pacific NW	2%	100 in.	7%	5 dB	16 dB

For accommodation of 95% of CONUS population, use rain margin of 5 dB at 18 GHz and 15 dB at 30 GHz.

The rainfall for climate zone 6, the Pacific Northwest, is even higher (100 inches per year); however, most of it occurs from light rainfall cloud formations and the impact upon communications for 99.5% availability is slightly less than that of the gulf areas.

Fortunately only 4% of the CONUS population resides in climate zone 5 and only 2% in zone 6. About 47% of the population resides in zone 3, which includes the northeast and midwest regions. Rain attenuation of 4 dB is adequate at 18 GHz and 11 dB at 30 GHz. The distribution of zone 3 rainfall attenuation vs outage percentiles is given in Figure 4.2-14 for 18 GHz and in Figure 4.2-15 for 30 GHz. Several prediction techniques are listed.

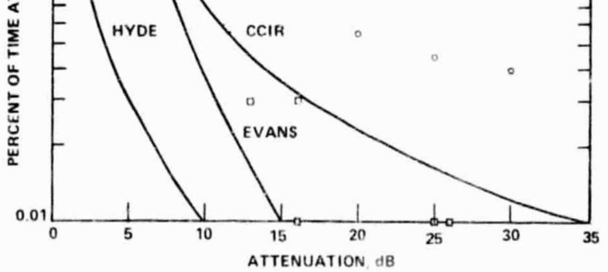


Figure 4.2-14. 18 GHz Rain Attenuation for Climate Zone 3

A summary of rainfall attenuation margins for various link availability levels is given in Table 4.2-9 for all six depicted rain zones. It is shown that an increase of about 10 dB is required at 18 GHz in order to raise the single earth station availability level from 99.5% to 99.9% and about 20 dB is required at 30 GHz. Margins of 50 dB (18 GHz) and 110 dB (30 GHz) would be required for 99.99% communications availability, which is not feasible for economic considerations.

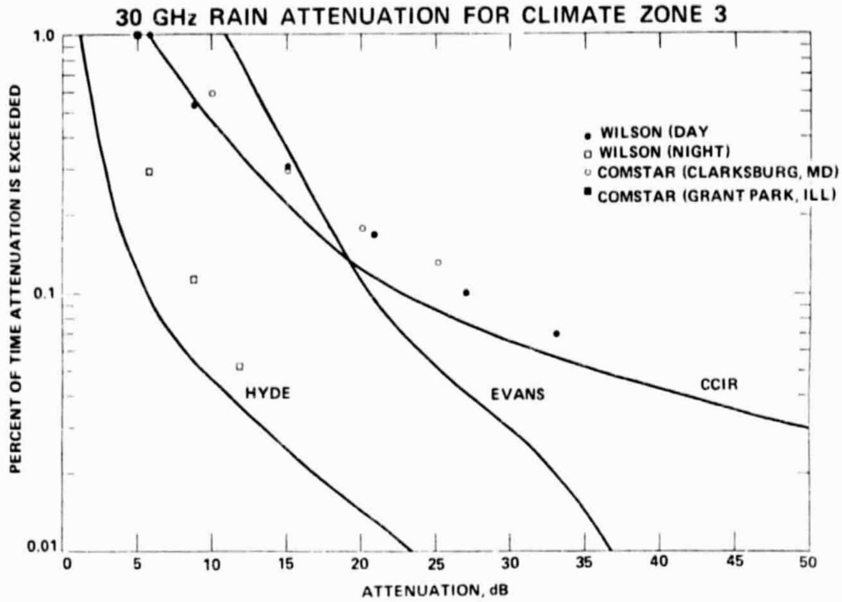


Figure 4.2-15. 30 GHz Rain Attenuation for Climate Zone 3

Table 4.2-9 Propagation Attenuation (dB) for the Six Rain Zones of CONUS

Transmission Frequency	Single Link Availability (Percent)	Rain Zone					
		1	2	3	4	5	6
18 GHz	99.0	1	2	2	3	3	4
	99.5	2	3	4	5	7	5
	99.9	4	7	8	13	19	10
	99.95	6	9	13	20	26	12
	99.99	13	23	35	49	54	28
30 GHz	99.0	2	6	6	8	8	12
	99.5	5	8	11	14	17	16
	99.9	13	17	24	38	50	26
	99.95	18	25	35	65	75	34
	99.99	36	66	86	111	121	75

The link equation for DTU application must be evaluated in detail for the particular geographic location of the terminal. Not only is the rain attenuation a variable, but also the view angle to the satellite and the location of the terminal relative to the on-axis peak of satellite antenna coverage beams will affect performance.

As an average value for the general link budgets of paragraph 4.2.2 it is estimated that 99.5% communications availability may be made available to 95% of all CONUS user locations if a rain margin of 5 dB is incorporated at 18 GHz and 15 dB at 30 GHz.

Rainfall and Outage Patterns

The impact of rainfall outage is not uniform over time. One must also consider worst case years that may have twice the rainfall of average years, worst case months within the year, time of day (more storms in late afternoon and very early morning), and duration of the storm outages.

While the total outage time is important, it is also of interest to generate a model of the distribution of outages and of the durations of individual outages. For this purpose a simple storm model was generated based on weather statistics for one winter and one summer month for a city in rain zone 3. By performing a random simulation of rain occurrences, the number of 18 GHz outages and outage durations can be obtained for a range of transmission margins. The results are shown in Table 4.2-10.

Table 4.2-10. Storm Simulation Results for Chicago

18 GHz Margin (dB)	Month	Number of Outages	Total Minutes Outage	Percent of Month Availability
2.5	January	2	70	99.8
	July	18	595	98.7
5	January	1	30	99.93
	July	10	275	99.4
10	January	0	0	100.0
	July	3	65	99.8

It is shown that the outage is greater in July than in January, which is due to the high incidence of summer thunderstorm rain of high intensity. As the link margin is increased the percent link availability is also increased.

The effect of rain attenuation as a function of hour of day is given in Figure 4.2-16. The morning peaks are keyed to the winter months and the afternoon peaks to the summer months. If the impact of outage is to be minimized, it may be of value to schedule teleconferencing meetings (for example) during the earlier periods of days during the summer months.

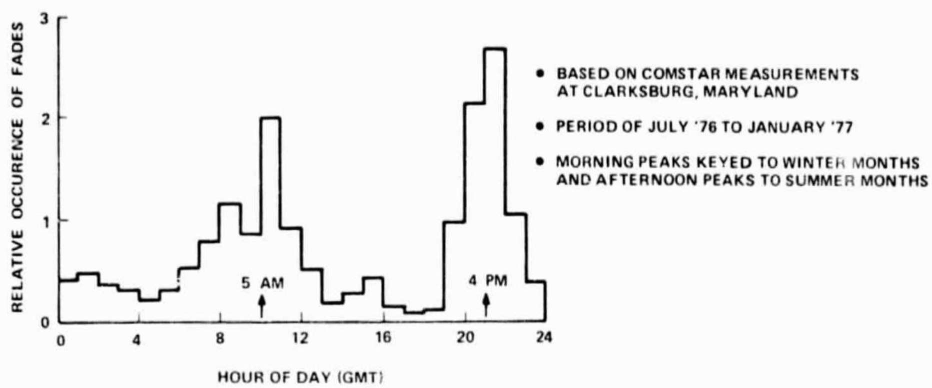


Figure 4.2-16. Diurnal Distribution of Fades Greater Than 5 dB at 19 GHz

Storms of high rainfall intensity are of short duration. It is shown in Figure 4.2-17 that a storm duration of about 18 minutes is normally associated with a rainfall rate of 0.6 inches per hour, which normally occurs less than 0.1% of the time in the Washington, D.C. area.

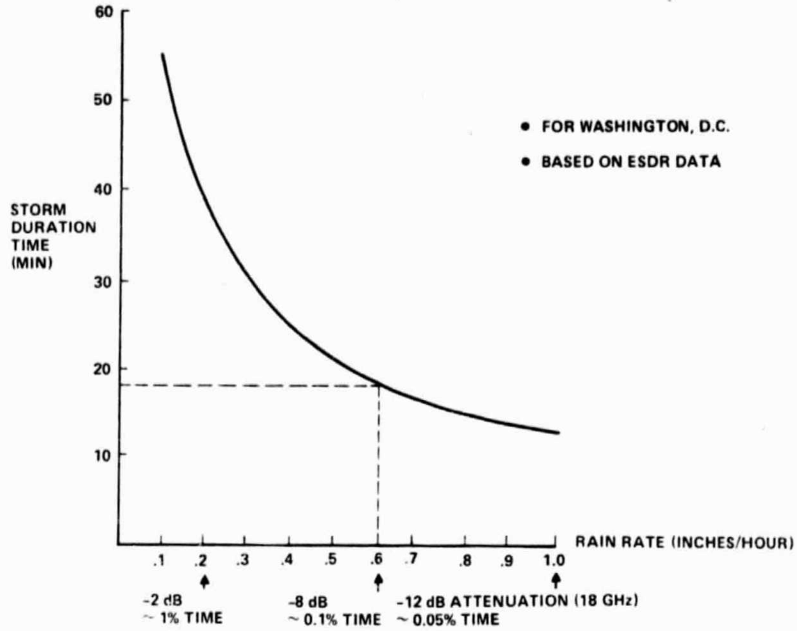


Figure 4.2-17. Rain Rate Duration Time

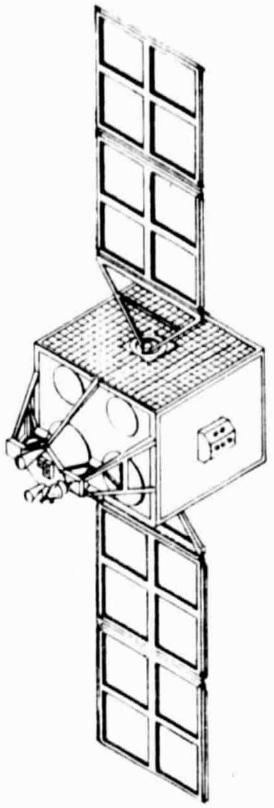
4.2.3 Spacecraft Segment

The configuration of the spacecraft for the baseline DTU system is largely determined by the requirements of CONUS coverage with overlapping antenna beams, a communications subsystem with 625 W rf power, 10-year on-orbit lifetime, and shuttle compatible launch.

One design approach using three-axis spacecraft stabilization is depicted in Figure 4.2-18, and additional layout details are shown in Figure 4.2-19. The baseline spacecraft is expected to have an on-orbit weight of 2650 lb including sufficient fuel for the 10-year design lifetime. The length of the spacecraft is 15 ft, and an additional 6.5 ft is required for a perigee motor. This combination would utilize about one-third the length capacity of the shuttle.

The spacecraft and launch weight budget of Table 4.2-11 shows a total weight in the shuttle of 16,105 lb. This is about 25% of the 65,000 pound total weight capacity of the shuttle. The costs of the shuttle part of launch are proportional to the greater of the utilization of total weight or length capacity. It is seen that the baseline DTU configuration is length constrained rather than weight constrained in determining shuttle cost allocation.

Solar array power of 4400 W is required at the beginning of the 10-year on-orbit life in order to support the 625 W rf communications power. Twin solar paddle appendages, each about 37 ft long by 8 ft wide, would provide this power. A more complete breakdown of spacecraft power allocation is given in Table 4.2-12.



ON-ORBIT WEIGHT	2650 lb
LENGTH	15 ft
MAXIMUM ARRAY POWER	4.4 kW
RF POWER	25 W/BEAM
ANTENNA	25 BEAMS, 1° EACH
PERIGEE MOTOR	SPM-4
UNIT SPACECRAFT COST	$36M

Figure 4.2-18. Spacecraft for DTU System

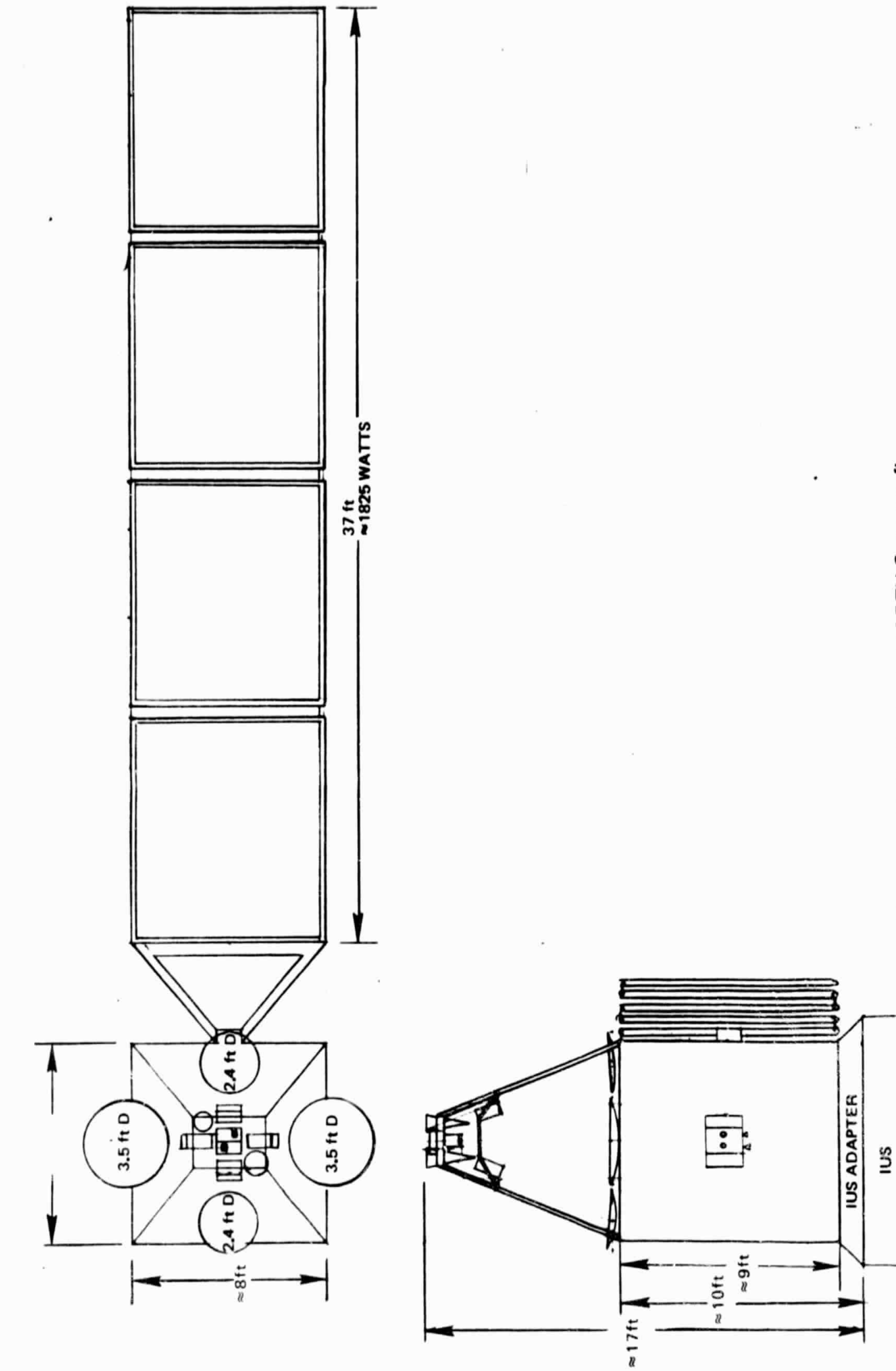


Figure 4.2-19. Profile Layout of DTU Spacecraft

Table 4.2-11. Spacecraft and Launch Weight Budget

	Weight	
	(lb)	(kg)
Spacecraft subsystems		
Communications	958	435
TT&C	50	23
Electrical power/electrical integration	481	218
Structure/thermal/mech integration	471	214
Attitude control/propulsion	237	108
Spacecraft dry weight	2,197	999
On-orbit fuel for 10 year life	449	204
Spacecraft launch weight	2,646	1,203
Transfer orbit system (SPM)	12,910	5,856
Cradle	550	249
Total weight in shuttle	16,105	7,309

Table 4.2-12. Spacecraft Power Budget

	Power (W)
Power amplifiers (25 of 25 W RF)	2085
Other communications subsystems	509
Other spacecraft subsystems	305
Battery charging	150
Total spacecraft load	3048
Array design margin (5%)	153
Allowance for degradation of cells (10 years)	1184
Total array output (BOL)	4385
The physical size of the solar array required is 29 m^2	

Spacecraft Communications Subsystem

A layout of the communications subsystem configuration for the baseline DTU system is shown in Figure 4.2-20. The odd-numbered uplink beams, which have vertical polarization, are combined and amplified with a wideband amplifier. A spacecraft noise figure of 8 dB or less may be achieved. The even-numbered uplink beams, which have horizontal polarization, are received in a separate uplink spacecraft antenna. This maximizes the isolation between adjacent antenna beams.

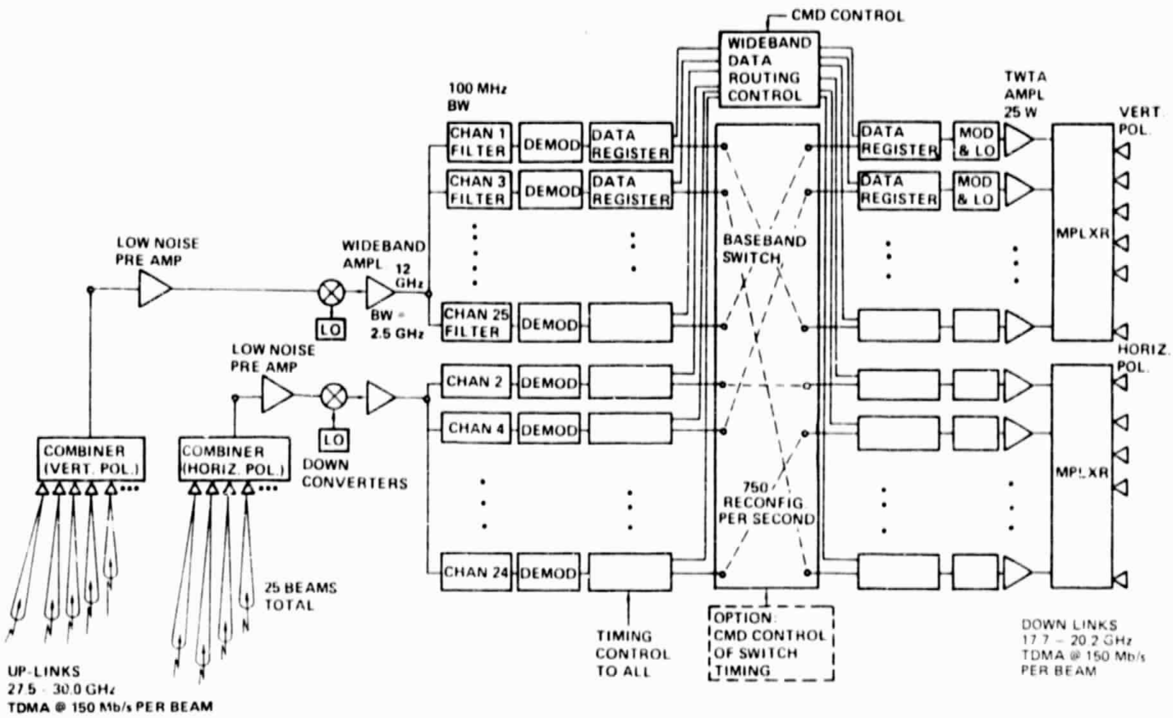


Figure 4.2-20. DTU Communications Subsystem

Passband filters of 100 MHz to 200 MHz bandwidth are then used to isolate the 150 Mb/s modulated uplink signals received from each uplink beam. Individual channel demodulators are used to obtain the 150 Mbs baseband burst rate per beam. The signals are passed to a data register in order that the last 25% of each communications interbeam data block may be routed and switched separately. This is the 6.3 Mb/s wideband data, which is limited to a maximum of six uplink transmissions and six downlink transmissions per beam. Command control may be employed in order to control the routing and network configuration of the wideband data. It is possible to have a single uplink communicate to all 25 of the downlink beams simultaneously; however, this would use one-sixth of the total system wideband capacity.

The medium rate and low rate data stream routing is controlled by a baseband switch. The switch interconnects the matrix of uplink beams and downlink beams in a cyclic manner. The frame rates for the baseline configuration, as discussed in paragraph 4.2.1, require that the switch operate at a speed of 750 matrix interconnects per second. This is within the limits of switching technology because the time per interconnect can be reduced to as low as 20 to 50 ns. The frame timing merely requires than an interconnect be achieved within 10 μs and is set by keeping the timing penalty to less than 1% impact on overall data rate capacity.

The three classes of signals are again combined in a data register, and the video baseband signal at 150 Mb/s burst rate is used to modulate an rf carrier with QPSK techniques. Each of the 25 downlink signals is separately amplified in a 25 W TWTA amplifier. Half of the beams are multiplexed, combined, and transmitted with vertical polarization and the other half with horizontal polarization. All transmissions occur within the downlink passband of 17.7 GHz to 20.2 GHz.

Master Control Facility and TT&C

The control facilities for a DTU satcom system could be located at a single site (Figure 4.2-21). This facility would consist of the following:

a. TT&C for control of housekeeping functions associated with spacecraft on-orbit positioning, antenna pointing, eclipse operations, etc, over a 10-year period.

b. TT&C for control of the spacecraft communications configuration. This optional feature is necessary if controls to wideband data link network distribution or changes to dwell period for selected antenna beam pair combinations are required.

c. Communications access control of a demand assignment used to allocate TDMA time slots.

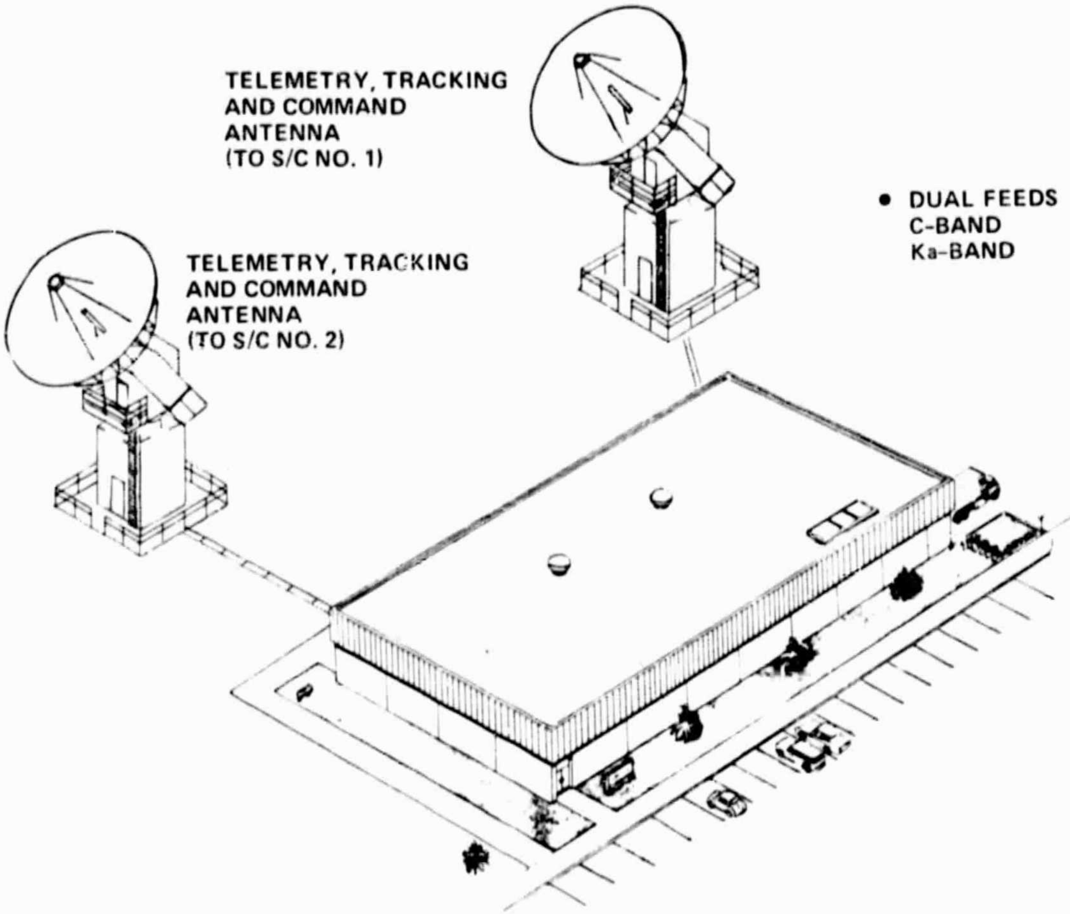


Figure 4.2-21. Master Control Facility and TT&C

If an operating and a backup spacecraft are required on orbit, then a dual antenna configuration would probably be implemented in order that TT&C may be continually achieved to both spacecraft. A dual feed to permit TT&C operation at either C-band or K_A-band would be a desirable feature in order to minimize the effect of rain attenuation at 18/30 GHz.

Launch and Transfer Orbit

The baseline DTU spacecraft has an expected initial on-orbit weight of about 2650 lb. A perigee motor is required to take the spacecraft from the shuttle to synchronous equatorial orbit. As shown in Table 4.2-13, the spacecraft weight exceeds the capacity of the current SSUS-A perigee motor by 175 lb. It is possible that an upgraded SSUS-A would meet the desired payload requirement, but if not, then a four-tank spacecraft propulsion module (liquid propellant) could be readily designed to meet the payload requirement for about the same recurring cost of $5 million per motor.

Table 4.2-13. Launch and Transfer Orbit Configurations

Perigee Motor	S/C On-Orbit Weight (to sync. equatorial)	Cost($78)
SSUS-D	Up to 1,565 lb	$ 2.5 M each
SSUS-A	Up to 2,475 lb	$ 5
SPM (4 tank)	Up to 2,930 lb	$ 5
SPM (6 tank)	Up to 4,390 lb	$ 6
SPM (8 tank)	Up to 5,850 lb	$ 7
IUS	4,000 to 5,000 lb	$13

Shuttle Cost Allocation

- S/C Design configuration length determines shuttle cost allocation for the baseline trunking FDMA, TDMA, direct-to-user TDMA systems
- S/C launch weight determines shuttle cost allocation for the baseline direct-to-user FDMA system

The interim upper stage (IUS) perigee is not designed to accommodate low weight spacecraft in an economic manner and unit costs would be twice as great.

4.2.4 Earth Terminal Segment

The baseline DTU configuration is based on the use of a single earth terminal at each user location. The size of the terminal antenna is small (less than 5 m diameter) in order to reduce the costs associated with installation, spacecraft tracking, and reflector/pedestal equipment. It is expected that a network of 1000 to 10,000 user terminals would be deployed throughout CONUS.

The baseline user terminal installation is given in Figure 4.2-22. A radome covering may be utilized in severe climate regions. All rf and baseband equipment is located in a colocated shelter. A self-contained operation would also require auxiliary equipment to generate about 8 kW of power. A low cost hour angle/-declination pedestal mount as shown in Figure 4.2-23 is used to orient the reflector boresight to the approximate spacecraft position on-orbit.

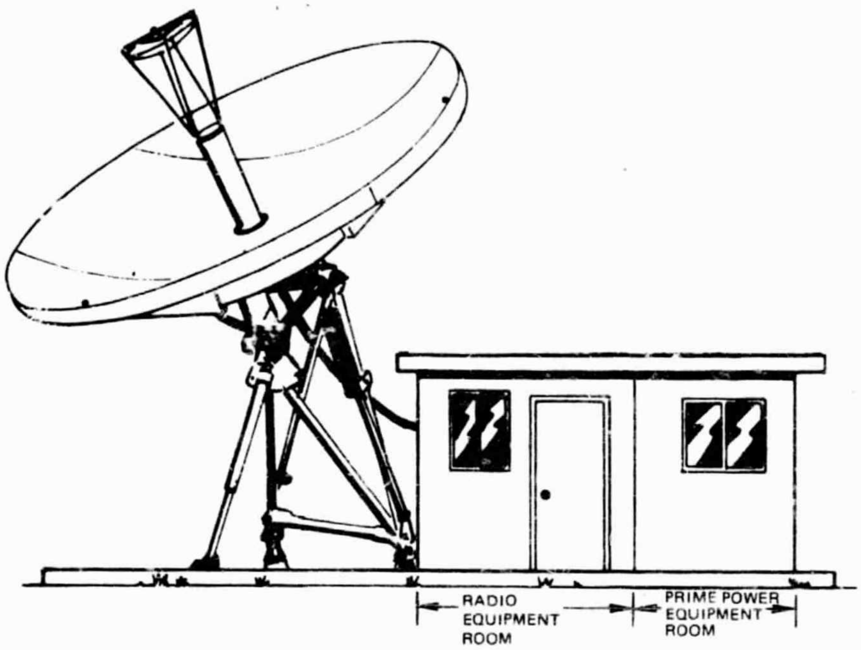


Figure 4.2-22. DTU Earth Terminal Installation

The baseline design utilizes a reflector diameter of 4.5 m. This generates a halfpower beamwidth of 0.26° at 18 GHz and 0.16° at 30 GHz. A steptrack antenna pointing system is used to point the user antenna to within 1 dB of peak gain. If larger reflectors were utilized (eg, 6 m diameter), then monopulse tracking would be required to maintain low tracking losses.

The key parameters of the DTU baseline terminal are listed below. The associated parameters are required in order to meet the link budget allocations given previously in paragraph

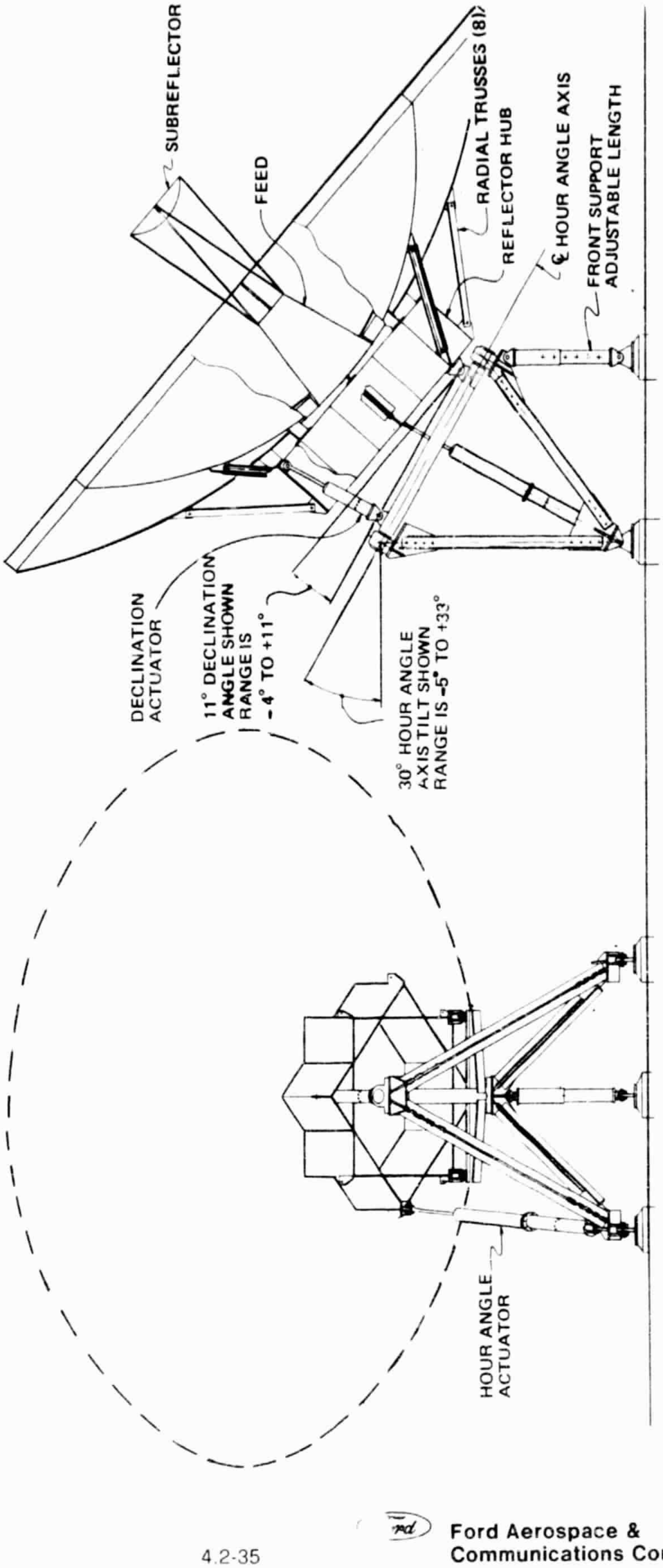


Figure 4.2-23. Hour Angle Declination Pedestal Mount

4.2.2. A block diagram of a standard terminal configuration is given in Figure 4.2-24.

a. Operations

1. Simultaneous transmit within 27.5-30.0 GHz band and receive within 17.7-20.2 GHz band
2. Dual polarization (horizontal and vertical)

b. Reflector

1. 4.5 m diameter
2. 60.4 dB transmit gain (peak)
3. 57.0 dB receive gain (peak)

c. Pedestal/Tracking

1. Hour angle declination mount
2. Step tracking with accuracy of 0.05°

d. Receiver

1. Uncooled parametric amplifier (230 K)
2. Demodulate to baseband of 140 Mb/s

e. Transmitter

1. 100 W TWTA in normal mode
2. 1000 W variable power TWTA during heavy rain

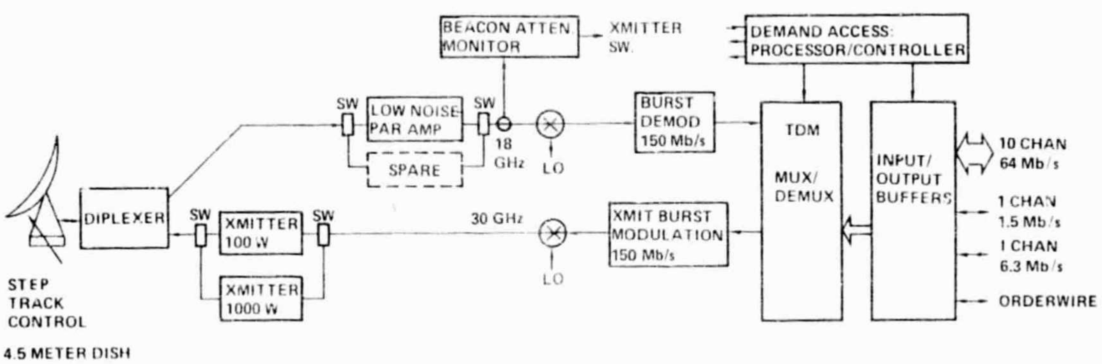


Figure 4.2-24. Standard DTU Terminal Configuration

The transmit and receive frequencies for all terminals within a given coverage beam area are fixed. The passband required to transmit/receive the 150 Mb/s QPSK burst rate is about 100 MHz. Each of the 25 beams would be assigned a unique 100 MHz of spectrum for the first generation system. If additional system data capacity were required, then frequency reuse could be empoyed for coverage beams which are spatially separated by several beamwidths. To achieve greater isolation, about half of the beams would contain terminals using vertical polarization and the other half of the beams would use horizontal polarization.

The 4.5 m diameter reflector is expected to generate 60.4 dB (peak) of transmit gain and 57.0 dB (peak) of receive gain. A moderate steptracking accuracy of 0.05° is required to maintain tolerable losses in pointing.

The terminal receiver utilizes an uncooled parametric amplifier with a noise temperature of about 230 K. This performance could be improved by using more costly cooled devices; however, the overall satcom link is uplink constrained rather than downlink; hence better performance by the receiver is not necessary. A redundant low noise receiver amplifier is installed in order to maintain high reliability.

The communication signals are amplified with a 100 W TWT amplifier during clear weather conditions. During heavy rainfall periods a 1000 W TWT power amplifier is utilized. A monitor of the attenuation of the spacecraft beacon signal is used to control 3 dB backoff steps for operation during moderate rainfall periods. This requires correlation of the attenuation at 18 GHz (beacon signal) with attenuation at 30 GHz (earth terminal transmitter).

The received rf signals at 18 GHz are downconverted, and a burst demodulator is employed to recover the 150 Mb/s burst rate. Subsequent TDM demultiplex and buffers are used to recover transmission signals at 64 kb/s, and/or 1.5 Mb/s, and/or 6.3 Mb/s. A multiple number of low-data-rate signals are received (or transmitted) from a single earth terminal. The timing of a demand access method of operation is achieved by a processor/controller unit. A separate orderwire signal is used to communicate the requests and control information.

4.2.5 Costs of Baseline DTU System

This section defines the guidelines for costing of a baseline satcom DTU system, determines satellite segment (spacecraft, launch, and TT&C) costs, earth terminal costs, and composite 10-year program costs including equivalent circuit costs. A summary of the baseline configuration, system costs, and circuit costs is given in Table 4.2-14.

Table 4.2-14. DTU Baseline Configuration

Configuration:	3.5 GB/s maximum capacity		
	25 beam full CONUS coverage		
	TDM @ 150 Mb/s per beam		
	Remodulation & antenna switching in S/C		
	1,000 earth terminals of 4.5 meter diameter		
System Costs:	Spacecraft	$248 M	27%
	Launch and TT&C	$ 85 M	
	Earth terminals fixed	$522 M	73%
	Earth terminals operations	$376 M	
Circuit Costs:	Duplex 64 kb/s channel	$ 7,500/yr	
	Simplex 1.5 Mb/s channel	$ 87,000/yr	
	Simplex 6 3 Mb/s channel	$365,000/yr	

Because the large number of earth terminals dominates the system costs, a special examination of reduced costs associated with quantity production is included.

4.2.5.1 Guidelines for Costing of Satcom System

The program implementation assumptions for costing of the 18/30 GHz DTU satcom

system elements are summarized in Table 4.2-15. The system cost factors delineate a 10-year operational system life with no residual salvage value. If design obsolescence is precluded, then it is likely that the terminals would really have a significant value at the end of the 10-year operating period and the remaining spacecraft capacity on orbit plus unlaunched spare would also be of economic value.

Table 4.2-15. Guidelines for Costing of DTU Satcom System

System Costs

a. Base on 3 year development period and 10-year operational system life.

b. Base costs on 1978 dollars as reference.

c. Assume zero residual salvage value of satellites and terminals at end of 10-year operational program life.

Satellite Costs

a. Assume four-satellite program (refurbished qualification model and three flight units).

b. Assume all satellites manufactured within 4 years from program go-ahead.

c. Assume on-orbit TT&C from a new dedicated TT&C facility.

d. Spacecraft to have 10 year design life with 10-year expendables.

Launch Costs

a. Assume shuttle launch, with full shuttle costs of $27 million in 1978 dollars.

b. Assume only three launches must be made over 10-year program and that no more than one satellite is launched per shuttle flight.

c. Assume insurance costs on successful satellite launch at 10% of spacecraft costs.

Earth Terminals

a. Terminals to be fabricated in production runs of 50 to 100.

b. Terminal costs to include transmitters, demodulation of 150 Mb/s TDMA data bursts, and modems for 10 channels of low rate data, 1 channel of medium rate data, and 1 channel of high rate data.

c. Earth terminals to have 15-year design life.

d. Spares and operations/maintenance are included. Design for unattended operation.

e. Land, utilities, roads, fences, auxiliary power, and radomes are not included.

The spacecraft costs are based on fabrication of three flight models and also refurbishing the qualification model of the development program in order to have a spare fourth spacecraft. The weight and costs of the spacecraft are based upon sufficient on-orbit attitude control fuel and sufficient equipment redundancy to meet a 10-year design lifetime.

The baseline earth terminal costs are based upon standardized terminals produced in lot quantities of about 50 to 100. Flexibility in modem implementation is provided.

4.2.5.2 Satellite Segment Costs

The spacecraft segment costs associated with a DTU system consist of the spacecraft development and fabrication; TT&C terminal development, fabrication, and operation for a 10-year period; the pro rata share of the shuttle launch costs; and perigee motors, which are required to take the spacecraft from the low orbit shuttle to a synchronous equatorial orbit.

Spacecraft Costs

The SAMSO developed spacecraft cost model was used to determine the costs associated with the baseline parameters of a DTU spacecraft. This model was based upon cost data

obtained from more than 15 satellite programs and has been progressively updated. A more complete description is given in the Appendix.

The flow diagram for application of the SAMSO cost model is given in Figure 4.2-25. The initial steps require generation of orbit parameters and spacecraft subsystem weight and power. The spacecraft launch weight and perigee motor selection are then made. Spacecraft costs are then generated for an average spacecraft implementation using subsystem weights as the driving parameters. The key parameters for the baseline DTU configuration using TDMA is given in Table 4.2-16. The next step is to apply complexity factors to both the development and fabrication of each of the subsystems relative to average case. This leads to the final cost estimating relationships (CERs) for both nonrecurring and recurring costs, as shown in Table 4.2-17.

Table 4.2-16. DTU Cost Model Input Parameters

Spacecraft Subsystem Weights	
Communications	958 lb
Structure/thermal	471 lb
TT&C	50 lb
Attitude control/propulsion	237 lb
Power (4385 W BOL)	481 lb
Launch Requirements	
Spacecraft launch weight	16,105 lb
Spacecraft & perigee motor length	21.5 ft

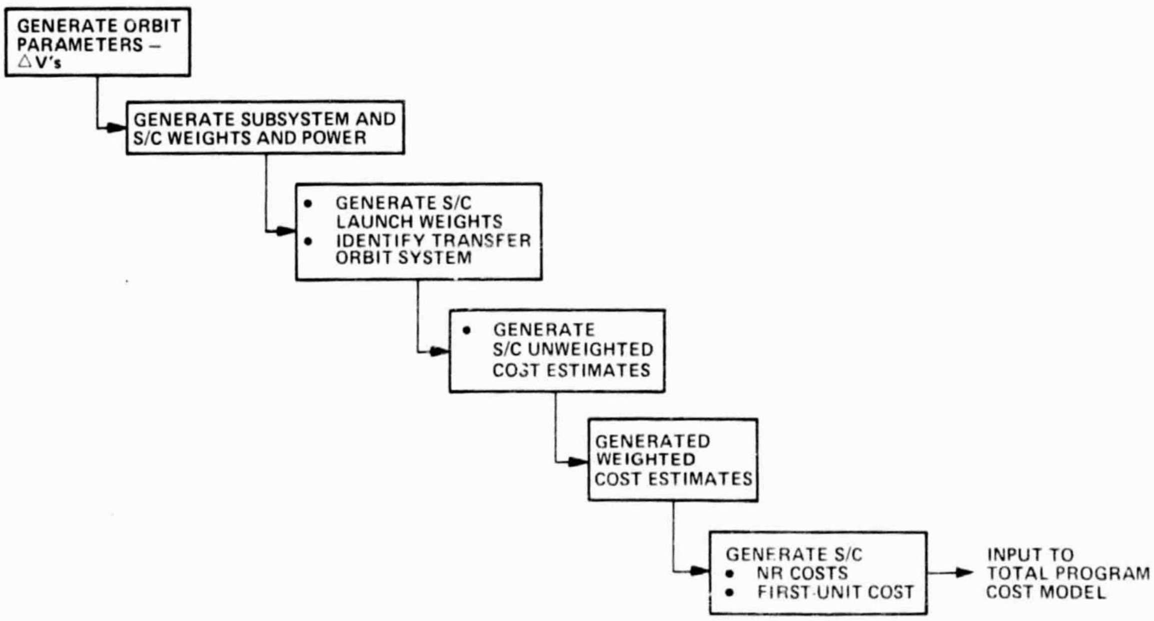


Figure 4.2-25. Spacecraft Cost Model Flow

Table 4.2-17. Derivation of Spacecraft Costs

Subsystem	Basic CERs		Complexity Factors	Final CERs	
	Nonrecurring	Recurring		Nonrecurring	Recurring
Communication (958 lb)	18,239	8.970	2.00 NR 1.87 R	36,541	16,773
TT&C (50 lb)	1,395	745	1.32 NR 1.18 R	1,846	882
Power Basic (481 lb)	6,283	1,058	1.00 NR 1.00 R	6,283	1,058
Array Cells	1,461	1,169	1.33 NR 4.64 R	1,942	5,427
AACS (237 lb)	10,324	3,271	1.25 NR 1.14 R	12,884	3,732
Structure (471 lb)	4,597	855	1.35 NR 1.38 R	6,188	1,178
	SAMSO Cost Model			65,684	24,050
			Mgmt and Support	19,704	7,262
				85,388	36,312

The shuttle pro rata costs are based upon the relative share of capacity utilization. The shuttle is expected to have a total bay length of 60 ft and a total weight capacity of 65,000 lb. The baseline DTU system is length limited rather than weight limited in determining the launch vehicle cost allocation. The base rates utilized for the shuttle are as follows:

Complete shuttle base rate (for 1978 dollars):

($18.22M x inflation factor relative to 1975) + $4.3M = $27.3M

Pro rata shuttle cost:

Base rate x 1.33 x pro rata based on 60 ft length or 65,000 lb weight = $36.25M.

The baseline DTU spacecraft segment costs for TDMA configuration are as follows:

Spacecraft

Nonrecurring	$85,388,000
Recurring unit cost	36,312,000
Prototype refurbishment and support	11,762,000

Perigee Motor

SPS-4 (or upgraded SSUS-A) unit cost	$5,000,000

Launch Vehicle

STS pro rata unit cost	$15,467,000

The total satellite development nonrecurring costs are $85,388,000 expressed in 1978 dollars. Each production model satellite would cost an additional $36,312,000.

The nonrecurring costs include a qualification model spacecraft. Refurbishing this unit to bring it up to flight qualified status is expected to cost an additional $11,762,000.

The unit pro rata share of shuttle (STS) launch is $15,467,000 and the unit cost of a perigee motor is $5,000,000.

A summary of total 10-year space segment costs is presented in Table 4.2-18.

Table 4.2-18. Total 10-year DTU Space Segment Costs (TDMA)

Item	Cost ($)	
Spacecraft (4)		
Development	85,388,000	
Refurbishment of qual model	11,762,000	
Three flight models @ $36.3M ea	108,936,000	247,086,000
Profit & on-orbit incentives	41,000,000	
Launch (3)		
Shuttle pro rata at 21.5 ft length	46,401,000	
Perigee motors (3)	15,000,000	61,401,000
TT&C (10 years)		
Development	3,400,000	
Terminal and control center costs	10,100,000	23,500,000
Operations @ $1.0M/year	10,000,000	
		331,987,000

4.2.5.3 Earth Terminal Costs

The earth terminal costs represent the largest segment of all overall system costs because of the large number of terminals in the network. Consequently, the unit cost per terminal is to be minimized for most tradeoff alternatives. A breakdown of the predicted terminal costs for the baseline DTU system is given in Table 4.2-19. The costs are shown in 1978 dollars for TDMA operation at 150 Mb/s burst rate. A production quantity run of 50 to 100 is assumed to take advantage of learning curve cost reduction. The cost tradeoff for key subsystem elements was described in paragraph 4.2.4.

Table 4.2-19. Standard Terminal Cost Elements

Item	Cost ($)	
Antenna		
4.5 m reflector, pedestal, feed & steptrack		20,200
Transmitters		
100 W power amplifier	32,100	
1000 W power amplifier	86,500	118,600
Receiver/Converters		
Low noise amplifier (2)	32,400	
Up/down converters	22,830	55,230
Digital Equipment		
Modulator/demodulator	39,800	92,870
Multiplexer/demultiplexer	12,570	
Demand assignment processor	40,500	
Other		
Frequency standard, orderwire, control monitor, racks, cabling, power	36,700	230,900
Other Site Equipment	64,700	
Installation and checkout	97,100	
Initial Spares	32,400	
		517,800

The total fixed costs for 1000 user terminals is about $522 million as shown in Table 4.2-20. An additional $40 million per year is required for operation of the control center and for operation, spares, and maintenance of the user terminals.

Table 4.2-20. Total Costs for 1000-Terminal Configuration

Item	Cost ($)	
Fixed		
System Development Engineering	3,770,000	522M
1,000 Terminals @ $518K Each	518,000,000	
Annual		
Control Center Operations	2,000,000	40M/Year
Operations, Spares, and Maintenance For Terminals	38,000,000	

4.2.5.4 Ten-Year Total DTU System Costs

The total 10-year satcom system costs in 1978 dollars for the baseline DTU system using TDMA are given in Table 4.2-21. The space segment cost including TT&C is projected at $332 million whereas the procurement and operation of 1000 user earth terminals are projected at $898 million.

Table 4.2-21. Cost Spread for DTU System

Program Element	Program Year												
	1	2	3	4	5	6	7	8	9	10	11	12	13
Spacecraft													
a) Spacecraft nonrecurring	43.8	21.9											
b) Spacecraft flight models (3)		43.6	43.6	21.8									
c) Prototype refurbish				3.6	3.6								
d) 3rd launch support								3.0					
e) Storage				0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
f) STS launch pro rata (3)	6.2	12.4	12.4			3.1	6.2	6.2					
g) Perigee motor (3)		5.0	5.0				2.5	2.5					
TT&C													
a) Nonrecurring	2.3	1.1											
b) Fixed hardware		5.0	5.1										
Earth Terminals (1000)													
a) Nonrecurring	2.5	1.3											
b) Fixed hardware		27.2	47.8	86.7	200.6	155.3							
Operating Costs													
a) TT&C operation maintenance				1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
b) Terminals operation & maintenance				37.6	37.6	37.6	37.6	37.6	37.6	37.6	37.6	37.6	37.6
c) Spacecraft orbit incentives				4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1
Yearly Totals	54.8	117.5	114.0	155.0	247.1	201.3	51.6	54.6	42.9	42.9	42.9	42.9	42.9

Note: All figures in millions of dollars normalized to 1978 value.

The cumulative cost buildup is illustrated in Figure 4.2-26. It is seen that 75% of the total 10 year costs are incurred by the end of the third year of operations because of the large initial fixed costs.

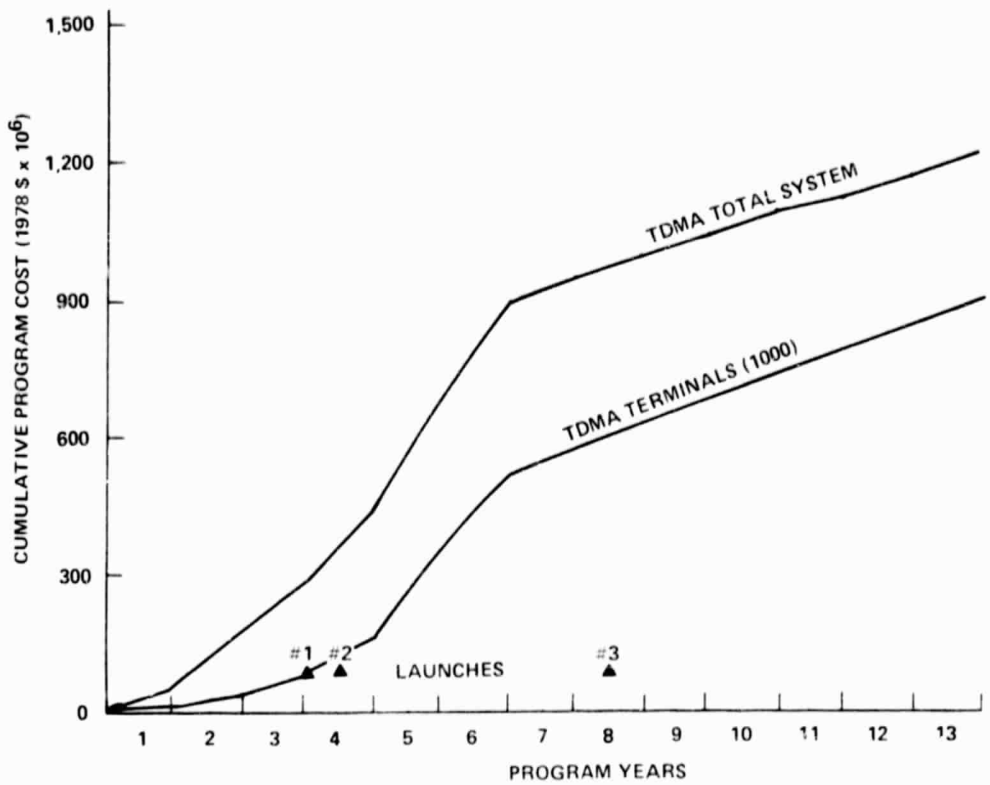


Figure 4.2-26. DTU Cumulative Costs

The total number of user terminals will significantly affect the total DTU program costs. As shown in Table 4.2-22, a 1000-terminal system would cost $1.234 billion whereas a 10,000 terminal system would cost $9.332 billion. A large number of terminals increases the interconnect network; however, timesharing of satellite data throughput capacity per terminal is reduced.

Table 4.2-22. Total 10-Year Satcom System Costs

Item	Cost for 1000 Terminals (M$)		Cost for 10,000 Terminals (M$)	
Spacecraft (4)	247		247	
Launch & Perigee (3)	61	27%	61	04%
TT & C	24		24	
Earth Terminal Fixed Cost	522		5,200	
		73%		96%
Earth Terminal Operations	380		3,800	
	1,234		9,332	

4.2.5.5 DTU Equivalent Circuit Costs

To establish the economic viability of a DTU satcom system at 18/30 GHz, it is desirable to establish approximate equivalent circuit costs. An approximation may be made within the constraints of a defined system and for a set of assumptions on key variables.

This paragraph defines annual circuit costs within the following set of constraints and assumptions:

a. *Satellite Network.* Implementation of DTU baseline design for TDMA operation with 25 beam coverage of CONUS and with 3.5 Gb/s throughput data rate. A four-satellite procurement and three-satellite launch are assumed over a 10-year operations period.

b. *Earth Terminal Network.* Implementation of 1000 user earth terminals, located in proximity of user facility. Antenna diameter of 4.5 m and terminals designed for unattended operation.

c. *TT&C and Control Facility.* A new TT&C and Communications Control facility is required with spares, maintenance, and operations for a 10-year period.

d. *Communications Outage.* Link design to permit 10^{-5} BER operation at 99.5% availability (44 hours outage per year) to 95% of all user locations within CONUS.

e. *Salvage.* No value to be placed on the residual satellite network capability or earth terminal capability at the end of the 10-year operating period.

f. *Cost of Money.* Because the initial system implementation expenses will gretly exceed the initial revenue, it is necessary to finance the net deficit. The cost of money may vary widely in the future; however, a value of 12% is assumed.

g. *Revenue Fill Factor.* It is typical that large systems are not operated at full capacity during the early years of service; however, as a first approximation, it is assumed that the revenue is constant over the 10-year period.

h. *Neglected Costs.* Other costs that are not included are:
   1. Rate-of-return to common carrier for organizing the network and assuming risk of successful operation
   2. Land/building costs associated with each terminal
   3. Interconnect costs from terminal modem to ultimate user location
   4. Inflation factors which escalate calculations based on 1978 value dollars

Within the above constraints and assumptions, the DTU system costs may be calculated as shown in Table 4.2-23. This shows a total fixed investment of $843 million and a required annual revenue of $184 million per year for the 10-year period.

Table 4.2-23. DTU System Costs

Fixed Investment		Required Revenue	
Space segment	$309M	Depreciation (10 yr)	$ 84M
TT&C	$ 14	TT&C OPS/maint.	$ 2
Terminals (1,000)	$520	Terminals OPS/maint.	$ 3[illegible]
		Cost of money (12%)	$ 60
	$843M		$184M/yr

The equivalent allocated circuit costs may then be determined as shown in Table 4.2-24. For example, the 64 kb/s service uses about 50% of the system data throughput capacity and hence is allocated 50% of the system costs. A peak capability of 25,000 simplex channels (25 beams of 1000 channels each) may be accommodated. This yields an annual circuit cost of $3700 (ie, 50% of $184 million per year divided by 25,000).

Table 4.2-24. DTU System Allocated Circuit Costs

Service	% System Capacity	No. of Simplex Channels	Annual Circuit Costs
64 kb/s	50%	25,000	$ 3,700
1.5 Mb/s	25%	625	$ 74,000
6.3 Mb/s	25%	150	$307,000

If each of the 64 kb/s channels is used 6 hours per day (4:1 peak/average and if two channels are required to support a digitized two-way voice link, then the cost while operating is $3.70 per hour.

In a similar manner, 625 channels at 1.5 Mb/s may be implemented for annual circuit costs of $74,000 per year. Finally 150 channels at 6.3 Mb/s would have annual circuit costs of $307,000. Note that these are costs allocated over circuit capacities and cannot be used directly to arrive at actual user costs or tariffs.

4.2.5.6 Subsystem Cost Tradeoffs

This paragraph examines the tradeoff relationship between cost and performance for the following elements of the direct-to-user earth terminal: (1) antenna subsystem, (2) high power amplifier, and (3) low noise receiver.

Antenna Subsystem

The antenna subsystem includes the reflector, feed assembly (including diplexer and rotary joint), pedestal, and support structure. If steptrack is required to point the antenna, then motors, gears, servos, and control logic are added. If monopulse tracking is required, a separate tracking receiver is included in addition to the extra feed assembly components.

Figure 4.2-27 shows the results of cost estimate studies performed by Fairchild (curves A, B), Communications Sciences Corporation (CSC) (curve C), and Digital Communications Corporation (DCC) (curve D) at K-band. The variance in results is partly due to variations in specification, and partly due to a general lack of experience in the industry in large production runs of antenna subsystems. All curves have been adjusted to 1978 dollars. Also shown in the FACC estimate for a K_U-band terminal.

Extrapolation from K_U-band to K_A-band is made by allowing for an increase of approximately 10% in reflection cost due to more acurate surface tolerance and an additional \$5000 for additional difficulties in machining the feed. The cost of adding steptrack is \$9000. The results of this extrapolation with steptracking added are the upper portion of Figure 4.2-27 for several levels of production quantity. The cost model used for the K_A-band antenna subsystem costs of Figure 4.2-27 is given by:

$$C_1 = 9.21\ D^{0.75} \qquad \$K \text{ for 1 terminal}$$

$$C_N = C_1\ (0.95)^{\log 2\ N} \qquad \$K \text{ for N terminals}$$

$$C_{100} = 6.55\ D^{0.75} \qquad \$K \text{ for 100 terminals}$$

where D is the antenna diameter in meters and steptrack is employed.

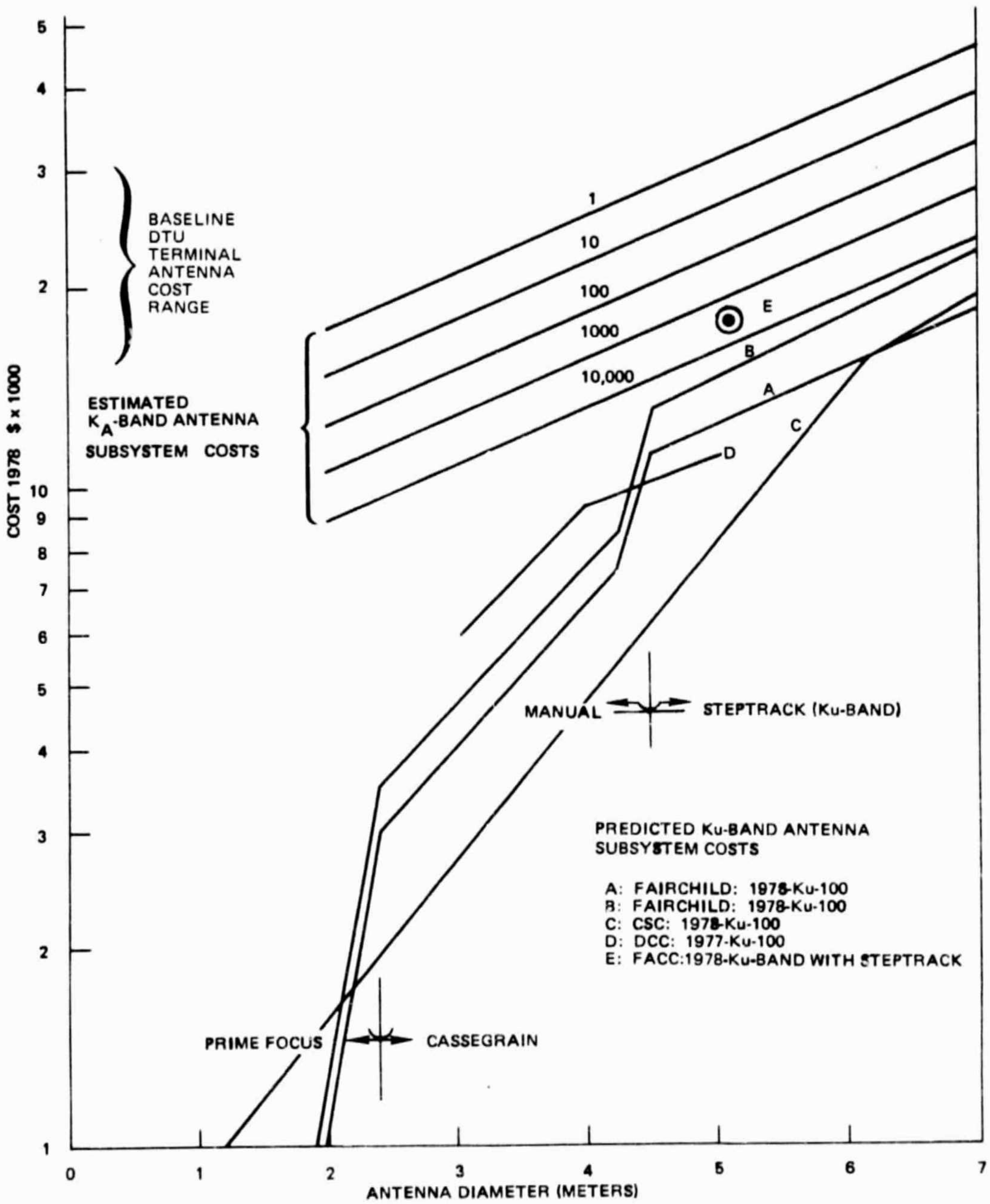


Figure 4.2-27. Antenna Subsystem Costs as Function of Reflector Diameter

The pointing loss predictions for fixed, steptrack, and monopulse track antennas are shown in Table 4.2-25 for various antenna diameters. This table shows that a fixed antenna may be a viable candidate if the satellite stationkeeping error could be reduced to 0.05° for earth terminal antenna diameters less than 3.5 m. This would reduce unit terminal costs by approximately $9000. At present, a 0.1° stationkeeping accuracy is the best achieved.

Table 4.2-25. Pointing Loss Performance of Fixed, Steptrack, and Monopulse Tracking Systems

	ANTENNA DIAMETER (m)									
	1	2	2.5	3	3.5	4	4.5	5	6	7
Frequency: 18 GHz										
Fixed:										
Stationkeeping ± 0.1°	0.2	0.6	1.0	1.5	2.0	2.6	3.3	4.0	5.8	7.9
Stationkeeping ± 0.05°	0.1	0.3	0.4	0.6	0.8	1.0	1.3	1.6	2.3	3.1
Steptrack	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.2	1.4
Monopulse	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Frequency: 30 GHz										
Fixed:										
Stationkeeping ± 0.1°	0.5	1.8	2.8	4.0	5.5	7.1	9.0	-	-	-
Stationkeeping ± 0.05°	0.2	0.7	1.1	1.6	2.2	2.8	3.6	4.4	6.4	8.7
Steptrack	0.9	1.2	1.4	1.6	1.8	2.1	2.3	2.6	3.2	3.9
Monopulse	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3

NOTES:
1. Fixed antenna pointing error equals satellite stationkeeping error plus 0.035°.
2. Steptrack pointing error equals 0.13 HPBW at 18 GHz plus 0.035°.
3. Monopulse pointing error equals 0.10 HPBW at 18 GHz.

However, for terminal diameters above 5 m, the steptrack pointing loss becomes excessive, especially at 30 GHz. The time constants of steptrack are typically in the order of 30 seconds. This is too long to track wind loading effects (especially wind gusts), which become an increasing significant factor with increased diameter. An angular error of 0.035° was assumed to account for wind loading and other antenna motion (building sway, vibration) with frequency components too high for steptrack to follow.

With monopulse tracking the principal pointing errors are caused by mechanical and thermal effects in the feed assembly and gain/phase unbalance in the electronics. A pointing error of 0.1° half-power beamwidth is generally achievable, leading to a pointing loss of 0.1 dB at 18 GHz and 0.3 dB at 30 GHz. Monopulse tracking is not recommended for the baseline DTU application, however, because the earth terminal cost is increased considerably. A unit cost increment of $50,000 per terminal might be expected over the steptrack terminal, to cover the cost of a four-element tracking feed, combining network, separate tracking receiver, and more precise pedestal and control electronics.

High Power Amplifier (HPA) Subsystem

HPA cost data was derived from two sources: (1) direct contact with vendors, and (2) extrapolation of data collected for K_U-band and HPAs. Direct contact of vendors proved to be of minimal value. Several companies (Hughes, Litton) were willing to discuss development K_A-band tube programs but not potential costs (after development) in production. Varian did provide an informal estimate in late 1978 for 200 W and 2 kW klystrons. This estimate is shown in Figure 4.2-28.

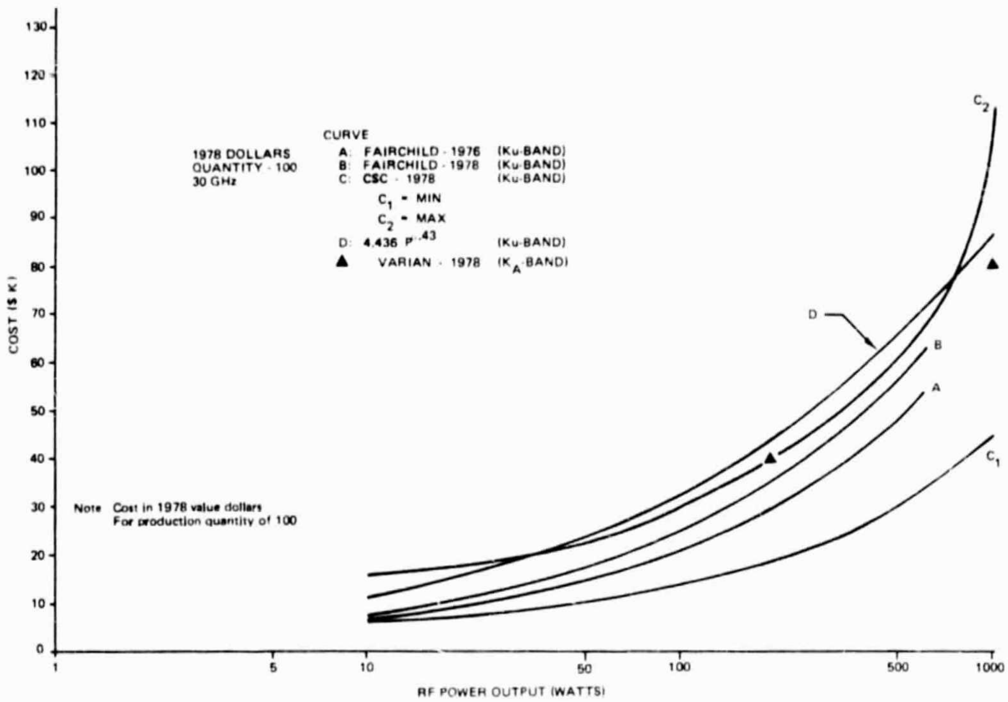


Figure 4.2-28. Unit Cost of High Power Amplifier as Function of RF Output Power

Extensive data has been gathered for HPAs at K_U-band (4 GHz). Two studies in particular, by Fairchild and CSC, were used. Since both studies were conducted in 1976, their costs were multiplied by 8% per year to convert to 1978 dollars. [Ref: (1) Kelly, Khatri, Kiesling, and Weiss, "Communication Systems Technology Assessment Study, Volume II Results," NASA CR 135224, Fairchild Space and Electronics Company; prepared for NASA Lewis Research Center, October, 1977. (2) Brown, Driver, Shameson, "Investigation of Small Earth Terminals," Communications Sciences Report 76/3023; prepared for NASA Goddard Space Flight Center, August 1976.]

Curve A of Figure 4.2-26 shows the Fairchild data in 1976 dollars. Curve B is the same data in 1978 dollars. Curves C_1 and C_2 are the CSC data in 1978 dollars with C_1 representing the minimum costs and C_2 the maximum cost. It can be seen that the Fairchild data (curve B) falls within the CSC bounds.

An extrapolation of HPA costs from K_U-band to K_A-band is somewhat subjective at this time. The tube and its cooling system are subject to the greatest cost differences, while the power supply, packaging, assembly, and test costs would remain relatively independent of frequency.

For this study, the HPA unit cost (curve D) was selected. This curve shows a cost increment of $4000 to $9000 over the Fairchild K_U-band data (curve B) and roughly matches the Varian estimates. Curve D is a plot of the equation:

$$C_{100} = 4.435\ P^{0.43}$$

where

P = HPA output power in watts

C_{100} = HPA unit cost in thousands of dollars for a production run of 100

The estimate of 30 GHz HPA costs as a function of power output for several production quantity levels is given in Figure 4.2-29.

Low Noise Amplifier (LNA) Subsystem

Figure 4.2-30 shows the results of the Fairchild study for the LNA (curve A), converted to 1978 dollars (curve B, assuming 8% per year inflation rate). The antenna temperature plus feed system losses of K_U-band were subtracted from the published data to show LNA temperature only.

The CSC K_U-band data is also shown in Figure 4.2-28 in 1978 dollars. The maximum CSC cost estimate is less than the Fairchild estimate for LNA temperatures below 140 K. The wide variance between the two studies may be attributed to the lack of experience in the industry in manufacturing significant quantities of LNA in this frequency band, especially at the lower temperature ratings where cooling is required.

LNA was contacted relative to supplying an LNA for 18 GHz. Two informal price estimates are shown in Figure 4.2-30. The 145 K LNA is a two-stage Peltier-cooled parametric amplifier, and the 185 K LNA ia a two-stage uncooled paramp.

Based on this data and the assumption that the FET and mixer technology now available at K_U-band will become available at 18 GHz within the next 5 years, the following cost-performance relationship was derived:

$$C_1 = 2451\ T^{-0.86}\ \$K$$

where

T = LNA temperature in kelvins

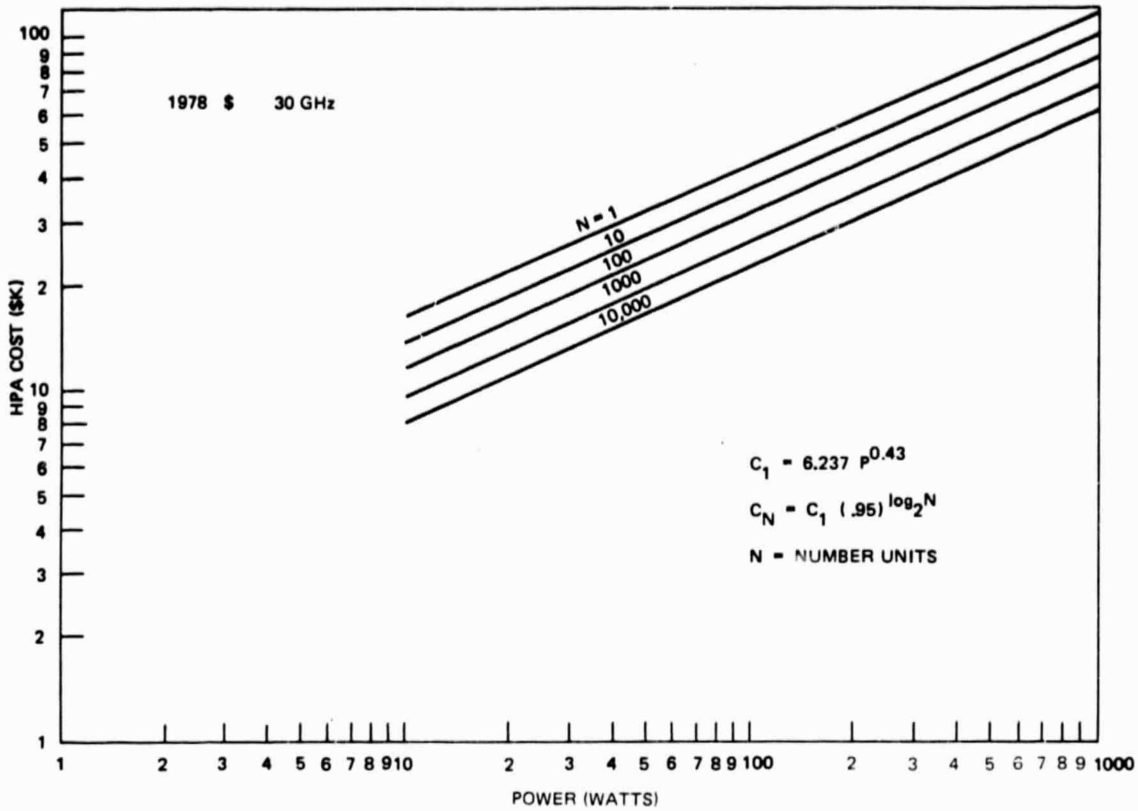


Figure 4.2-29. Estimate of HPA Costs as Function of Power Output

C_1 = LNA cost in thousands of dollars for one unit

For N units

$$C_N = C_1\,(0.95)^{\log_2 N}\ \$K$$

For 100 units

$$C_{100} = 1743\ T^{-0.86}\ \$K$$

The equation is plotted as curve D in Figure 4.2-29 and also in Figure 4.2-31 for several production lot sizes.

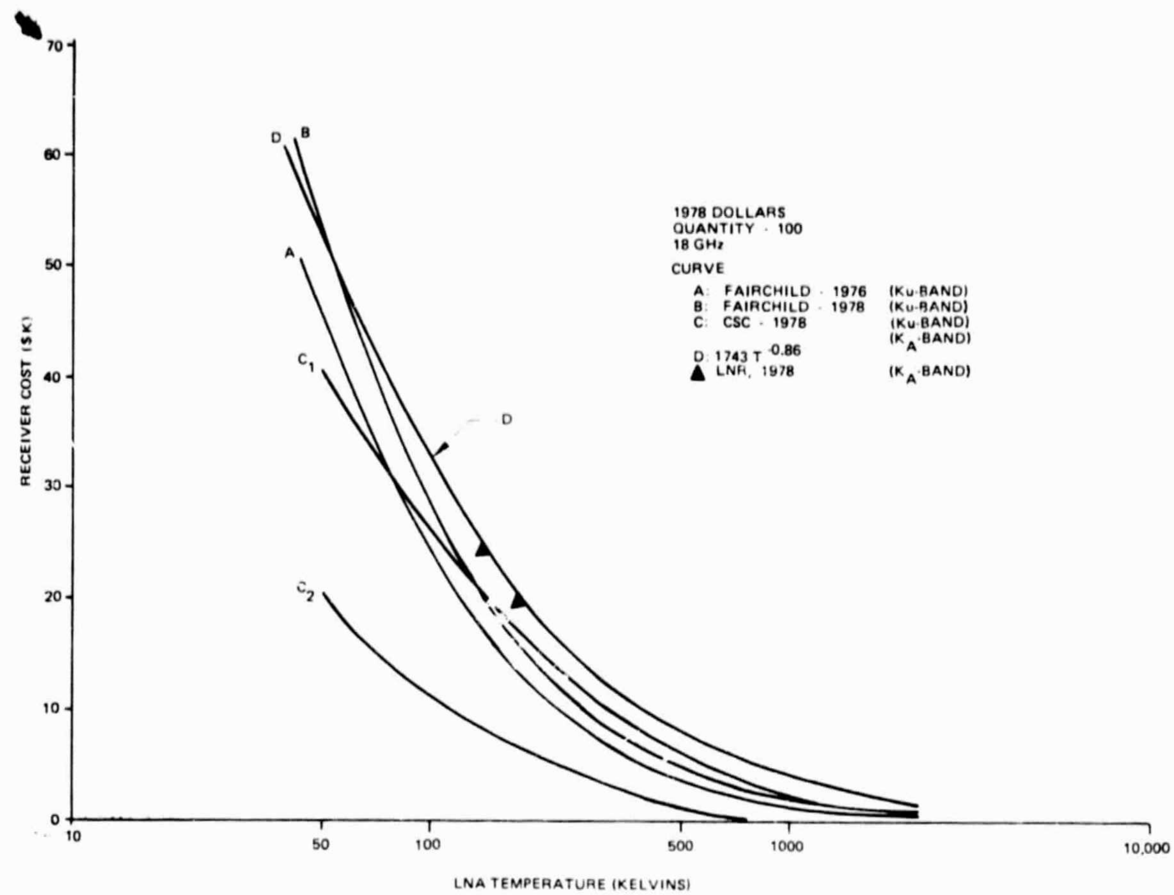


Figure 4.2-30. Low Noise Receiver Cost as Function of Noise Temperature

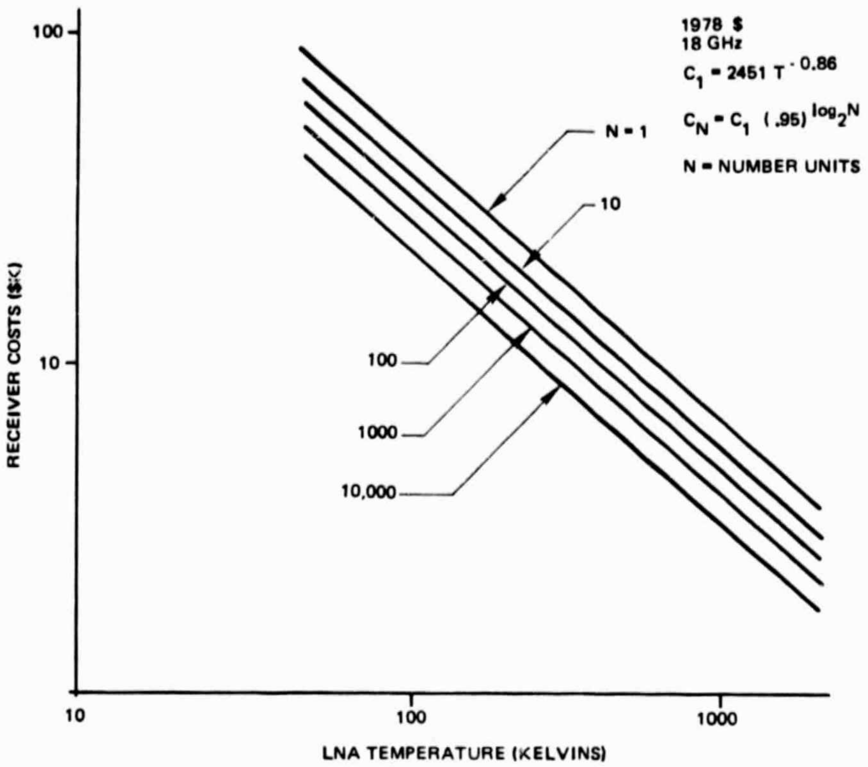


Figure 4.2-31. Low Noise Receiver Cost as Function of Noise Temperature

4.2.5.7 Reduced Costs for Quantity Production Runs

The costs of the earth terminal segment of the direct-to-user system dominate the total system as shown in paragraph 4.2.5.5. If the large quantity of up to 10,000 user terminals can be manufactured in sizable production runs rather than a few at a time per manufacturer, then appreciable cost savings may be obtained. This section examines manufacturing cost learning curve rates, which may be applicable to the low noise amplifiers, transmitters, and antenna subsystems of the earth terminal.

The baseline DTU earth terminal costs were based on the premise that the terminals would be produced in lot quantities of about 50 to 100. A relatively standard design is assumed; however, flexibility in the modem implementation (ie, number of channels and classes of data service) is provided.

Manufacturing Cost Learning Curve

It is common practice in economic studies to apply a standard learning curve to single unit costs in order to determine the per-unit cost for quantity purchases. This learning curve is defined by the following equation:

$$C_{pu} = C_{su} L^{\log_2 N}$$

where

C_{pu} = per-unit cost for quantity purchases of N units

C_{su} = single unit cost (N = 1)

N = quantity purchase

L = rate or percent of learning curve (When L = 0.95, for example, the resulting C_{pu} values are said to correspond to a 95% learning curve.) [Hatfield, B.M, "Satellite-Systems Cost Estimation," *IEEE Trans. on Comm.*, October 1974.]

For the present 18/30 GHz satcom study, relatively few pieces of K_A band hardware are currently available, hence price schedules for volume purchases are not established. Therefore, the learning curve rate will be determined from 1973 data for mature technologies, eg, LANs, HPAs, and antennas for C-band systems. The assumptions are that: (1) as the demand for K_A-band equipment increases (eg, due to bandwidth restrictions in the lower frequency bands), the requisite development and manufacturing resources will be committed by the respective device manufacturers. This commitment, in turn, will result in a ready availability of K_A-band equipment at competitive prices; and (2) aside from a generally higher price for K_A-band equipment, the K_A-band and C-band technologies are sufficiently similar to lead to similar pricing strategies. These assumptions are generally supported by marketing representatives and engineers in the several companies contacted.

Learning Curve Rate for Antenna Subsystem

The antenna subsystem of a DTU terminal would include the reflector, feed, pedestal and mounting structure, and tracking equipment.

Three antenna manufacturers were contacted for information on quantity discounts. Each had substantially the same response to the basic discount question, although one was reluctant to discuss specific pricing structure.

It was clear that there was not much current activity in the 20-30 GHz area, although all three companies indicated they were looking at the problems and design constraints. One individual estimated that manufacturing to within the necessary surface tolerances for 30 GHz operation would require machining from a large block of material and hence was not optimistic regarding a low-cost 4.5 m diameter antenna. All three manufacturers mentioned that large quantity purchases of antennas would result in lower per-unit antenna cost. One manufacturer stated that the price discounts for material, however, did not continue to increase once a buy for about 100 antennas had been reached. This manufacturer quoted the following approximate prices for 5 m C-band (4/6 GHz) antennas:

Small quantity	$8200 each
Quantities over 100	$5000 each

Another manufacturer stated the following approximate discount schedule:

Single unit	$P
50 units	$(0.75)P
100 units	$(0.70)P
500 units	$(0.65 to 0.60)P

Both of these schedules fit a standard 95% learning curve, as shown in Table 4.2-26.

The fit of the price schedule of manufacturer A with the 95% learning curve is, admittedly, approximate, unless one takes the approach used previously in determining the learning curve for LNAs. That is, when a learning curve is selected that minimizes the mean squared error between the quoted price schedule (ie, 1 = $8200 each, 10 = $8200 each, 100 = $5000 each, 500 = $5000 each, and 1000 = $5000 each) and the learning curve price schedule, the learning curve rate selected is 95%.

In view of the above, a learning curve rate of 95% has been selected for the antenna price versus antenna quantity calculation in this study.

Table 4.2-26. Comparison of Antenna Price Schedules with the Standard 95% Learning Curve

Quantity	Manufacturer A	Manufacturer B	Learning Curve (95%)
1 or Small number	P	P	P
50	-	0.75P	0.75P
100	0.61P	0.70P	0.71P
500	0.61P	0.65P 0.60P	0.63P
1000	0.61P		0.60P

In summary, then, the 95% learning curve will be used for all three components — antennas, LNAs, and HPAs. Associated price versus quantity information is given in Table 4.2-27 where price is given as a factor of the small quantity price.

Table 4.2-27. Per-Unit Price vs Quantity Purchase for a Standard 95% Learning Curve

Quantity	1 or small number	50	100	500	1000
Price	1.0	0.75	0.71	0.63	0.60

Learning Curve Rate for Transmitter Subsystem

Manufacturers contacted for price schedule information on HPAs for use as 30 GHz transmitters were in general agreement on the following points:

a. Current production of HPAs is usually in lot sizes of 10 to 20.

b. Buys in 100 lot quantities would get a 5% to 7% discount because of reduction in cost of material and in startup costs. The basic production lot would still probably be the 10 to 20 lot size.

c. When 200 to 300 or more units are required over some reasonably short interval (1 to 2 years), then reexamination of the assembly line procedures would be justified and could result in a discount of 20% to 25%.

A learning curve based on these points closely approximates a rate of 94% if (1) the single-unit cost, C_{su}, is taken as the cost associated with production lot sizes of 10 to 20 units; and (2) the quantity purchased, N, is divided by 20 prior to computing the per-unit cost, C_{pu}. For example:

a. If N = 100, then N/20 = 5, and $\frac{C_{pu}}{C_s} = 0.95^{\log_2 5} = 0.89$

b. If N = 300, then N/20 = 15, and $\frac{C_{pu}}{C_{su}} = 0.95^{\log_2 15} = 0.79$

c. If N = 500, then N/20 · 25, and $\frac{C_{pu}}{C_{su}} = 0.95^{\log_2 25} = 0.75$

This discount factor, ie, C_{pu}/C_{su}, for quantities of 100 is the only one that does not agree with the information presented earlier.

If these same discount factors (0.89, 0.79, and 0.75) are derived without using the artifice of dividing N by 20, then the learning curve rate must be increased to about 0.97. That is:

$$0.89 \approx 0.983^{\log_2 100}$$

$$0.79 \approx 0.97?^{\log_2 300}$$

$$0.75 \approx 0.968^{\log_2 500}$$

It should be noted that those companies that already have experience in large quantity programs (eg, Litton with the F-16) suggested overall learning curve rates somewhat less than did the custom houses. For this study, a rate of 95% seems appropriate. It is a compromise between the possible 97% rate noted earlier and a 90-95% rate suggested by some large volume companies.

Learning Curve Rate for Low Noise Amplifier Subsystem

Data for estimating the volume production costs of the low noise receivers for operation at 20 GHz is extrapolated from circa 1973 budgetary cost quotes for various C-band low noise amplifiers.

These rates are determined by minimizing, over various values of L, the mean squared error between the quoted cost values and the values given from the equation. For example, the squared error for the MITEQ device cost is given by

$$\overline{E^2} = \frac{1}{24} \sum_{N=1}^{24} \left(C_{pu,N} - 1100\, L^{\log_2}\right)^2$$

The value of L that minimizes E^2 is given in Table 4.2-28.

Table 4.2-28. Budgetary Costs and Associated Learning Curve Rates for LNAs

Manufacturer	Units	Quoted Cost/Unit	L
MITEQ (5 dB NF)	1-4 5-9 10-24	\$ 1100 1000 950	0.97
Micromega Div of Bunker Radio (140 K NF)	1 10 100 500	\$12000 10000 6000 4000	0.90
Amplica, Inc (870 K NF)	1 100 500	\$ 1800 1100 825	0.92
International Microwave Corp (520 K)	1 100 500	\$ 1125 775 650	0.93
Watkins-Johnson			0.95
	Salesman Estimate for K_a-Band LNA Devices		

Tables 4.2-29 and 4.2-30 show OEM prices for plastic semiconductor devices manufactured by Siliconix and optoelectronic devices manufactured by Hewlett-Packard, respectively. Depending on the component, the learning curve discount rates vary from 1.0 to about 0.90. Based on this information, a learning curve rate of 0.95 was selected for this study effort for LNAs.

Table 4.2-29. Siliconix, Inc, OEM Prices for Semiconductor Devices (15 March 1973)

PART NO.	1–99 PRICE	100–999 PRICE	1K PRICE
E100	$ .530	$ .400	$ .320
E101	.980	.740	.590
E102	.820	.620	.490
E103	.730	.550	.440
E105	4.330	3.250	2.600
E106	2.750	2.060	1.650
E107	2.920	2.190	1.750
E108	2.250	1.690	1.350
E109	1.650	1.240	.990
E110	2.650	1.990	1.590
E111	.650	.490	.390
E112	.580	.440	.350
E113	.650	.490	.390
E114	.650	.490	.390
E174	.820	.620	.490

Table 4.2-30. Hewlett-Packard OEM Prices for Optoelectronic Products (April 1973)

MICROWAVE INTEGRATED CIRCUITS	1-9	10-24	
35000A	150.00	134.00	
35001A	200.00	178.00	
35002A	292.00	248.00	
35005A	1200.00	1140.00	
35007A	490.00	460.00	
35007B	450.00	420.00	
35102A	800.00	725.00	
HIGH FREQUENCY TRANSISTORS	**1-9**	**10-24**	**25-99**
35820A (10 Chips)	150.00	125.00	125.00
35821B/E	19.00	19.00	19.00
35821E Opt. 200	40.00	40.00	40.00
35822B/E	19.00	19.00	19.00
35822E Opt. 200	40.00	40.00	40.00
35823B/E	19.00	19.00	19.00
35824A	12.50	12.50	12.50
35825B/E	19.00	19.00	19.00
35825E Opt. 200	40.00	40.00	40.00
35826B/E	19.00	19.00	19.00
35830A (10 Chips)	150.00	125.00	125.00
35831B/E	19.00	19.00	19.00
35832B/E	25.00	25.00	25.00
35833B/E	25.00	25.00	25.00
35834B/E	25.00	25.00	25.00

Subsection 4.3

Alternative FDMA Direct-to-User System

The use of frequency division multiple access (FDMA) modulation technique presents one of the key alternative concepts to the baseline TDMA system for direct-to-user (DTU) application. This section details tradeoffs, concepts, and costs of the FDMA approach.

4.3.1 Network Configuration

The relative advantages and disadvantages of FDMA systems in contrast to the baseline TDMA system of modulation are given in Table 4.3-1. The main advantage of FDMA systems is that communications to the spacecraft may be achieved at a transmission rate that matches the real information data rate of the individual user terminal. This reduces the peak transmitter power of the user terminal and precise time synchronization is not required.

Table 4.3-1. TDMA vs FDMA Tradeoffs

	FDMA	TDMA
Earth terminal transmitter peak power	Low	High
Precise time synchronization	Not required	Required
Transmission rate	Low	High
RF multiplexer losses	Increases with number of beams	None
Power loss due to backoff	4-6 dB	0-1 dB
Flexibility in interbeam connectivity	Limited by fixed channel bandwidths	High; vary by changing slot widths
Impact on satellite weight	High; especially with large number antenna beams & backoff	Moderate
Earth terminal data buffer storage	Not required	Required
Earth terminal cost	Lower for small number of simultaneous accesses	Lower for high number of simultaneous accesses

FDMA is a very good system if the number of simultaneous accesses to the spacecraft is small. However, with up to 10,000 user terminals coupled with multiple channel transmission per terminal the requirements for filtering and channelization within the spacecraft become excessive. The spacecraft weight is greater and associated spacecraft costs are higher.

The variance of an FDMA system to the baseline TDMA system is summarized in Table 4.3-2. The reliability of the spacecraft is improved because no on-orbit demodulation and remodulation is required; however, the flexibility to meet changing traffic patterns is reduced.

Table 4.3-2. Direct-to-User FDMA Configuration

Spacecraft Variance to Baseline

- Reliability improved because no demodulating in spacecraft
- Spacecraft filtering complex due to 625 input and output channels of 8 MHz bandwidth
- Spacecraft rf power/beam increased to 80 W because of multicarrier backoff
- Spacecraft weight increases by 1630 lb and unit cost increases $24M

Earth Terminal Variance

- Transmitter peak power levels reduced by 20 dB
- System becomes downlink constrained and antenna diameter remains constant
- Advanced frequency synthesizer required to match all downlink frequency slots
- Eliminates need for high-speed demodulator and data buffer
- Terminal cost increased

System

- Less flexibility to match changing traffic patterns

The system concept for DTU FDMA provides CONUS coverage with 25 beams. The total data rate capacity per beam is 140 Mb/s and hence the total maximum spacecraft data throughput capacity is 3.5 Gb/s. The control of channel access may be achieved on a fixed assignment basis or by demand assignment or a combination. Each user terminal has narrow-band transmitters associated with each service. Standard terminals would have 10 channels at 64 kb/s, one channel at 1.5 Mb/s, and one channel at 6.3 Mb/s.

The FDMA frequency plan is illustrated in Figure 4.3-1. Each uplink and downlink beam is assigned 200 MHz of bandwidth with two times frequency use in order to permit ease of filtering and to assure flexibility in expansion of data rates within destination channels. One set of channels is transmitted/received with horizontal polarization and the other with vertical polarization in order to maximize interchannel separation. The bandwidth assigned to each beam is divided into 25 destination channels of 8 MHz bandwidth each. This is sufficient to pass a wideband signal (if required) as well as low rate and medium rate data.

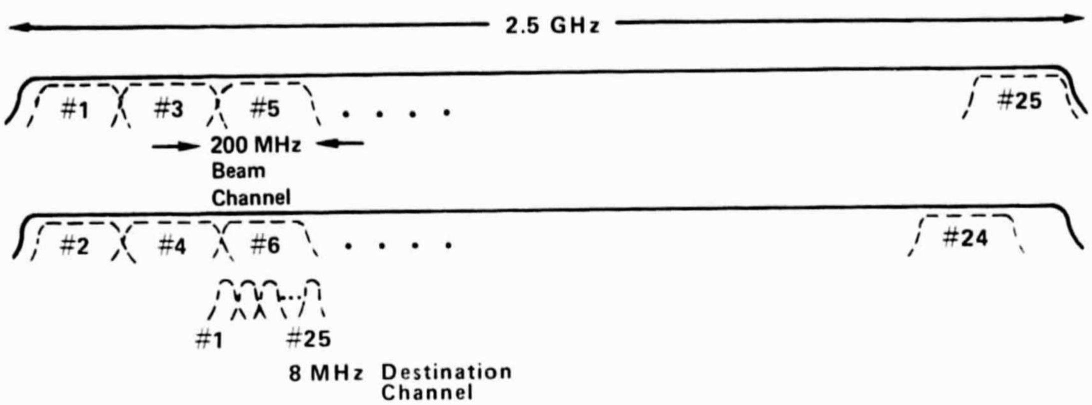


Figure 4.3-1. DTU FDMA Frequency Plan

If the extra flexibility in destination bandwidth is not required, then the destination channel bandwidth could be reduced to 4 MHz and the bandwidth per beam would be reduced to 100 MHz.

4.3.2 Spacecraft Configuration

The spacecraft transponder configuration for FDMA application is shown in Figure 4.3-2. Passband filtering is required in order to obtain 625 channels which have a fixed interconnect to 625 downlink channels. Demodulation to baseband is not required. Each group of 25 data channels associated with a particular downlink beam are multiplex combined and amplified with an 80 W TWT amplifier.

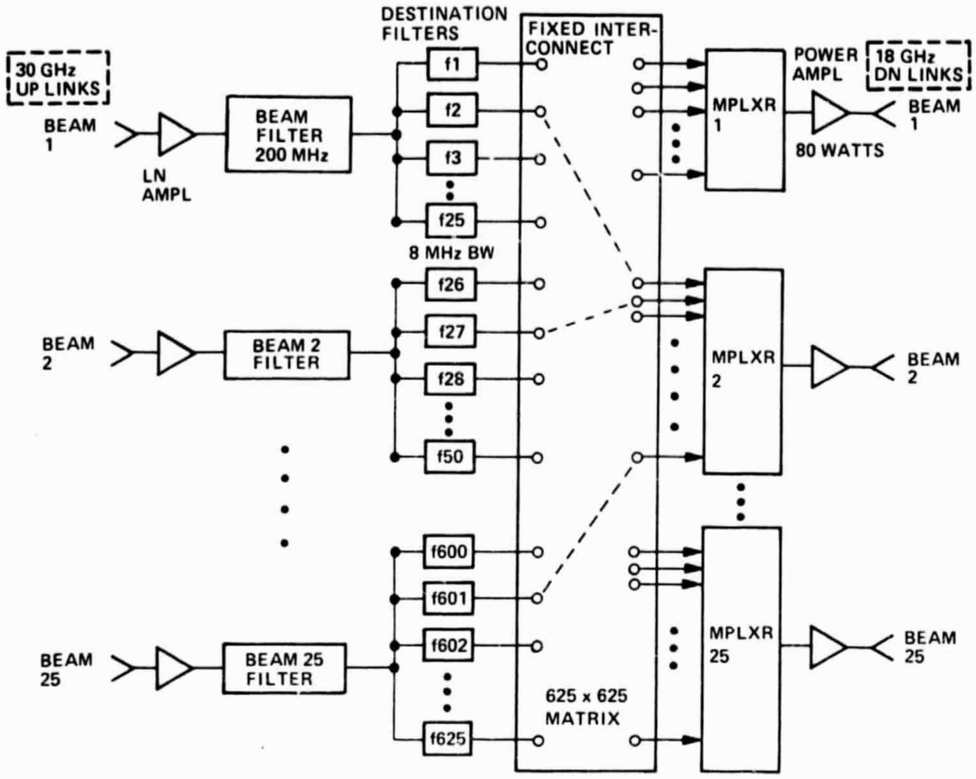


Figure 4.3-2. Spacecraft Transponder Configuration for FDMA Application

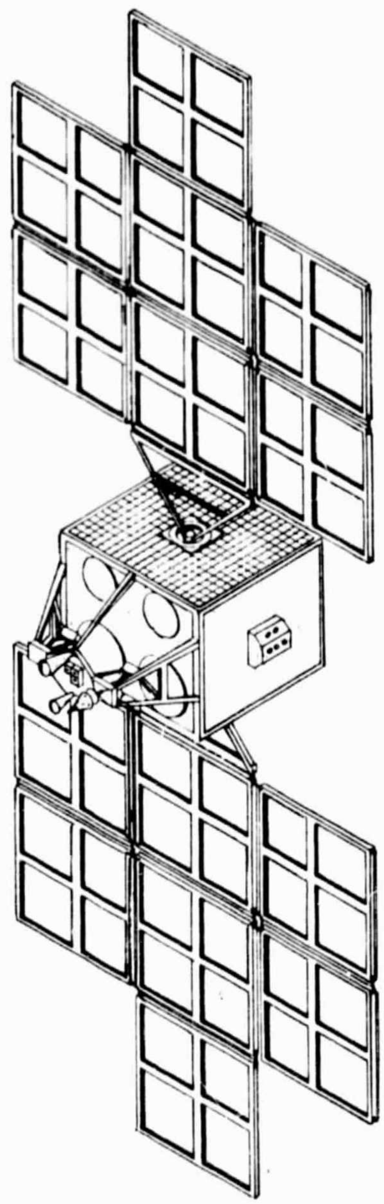
The weight of the extensive filtering network and higher amplifier power relative to the baseline increases the communications subsystem weight to 1392 lb and increases the on-orbit spacecraft weight to 4277 lb, as shown in Table 4.3-3. In addition a larger perigee motor is required, for example, SPM-8 (or IUS), and the total weight in the shuttle increases to 27,607 lb.

The total rf power is 2000 W and the total spacecraft requires an end of life solar array power of 8,135 W. A beginning of life solar power of 11,145 W is required to accommodate solar cell degradation over a 10-year period on orbit.

Table 4.3-3. Spacecraft and Launch Weight Budget (FDMA)

Item	Weight	
	(lb)	(kg)
Subsystems:		
Communications	1,392	633
TT & C	50	23
Electrical Power/Elect Integration	1,092	496
Structure/Thermal/Mech Integration	688	313
Attitude Control/Propulsion	288	288
Spacecraft Dry Weight	3,510	1,595
On-Orbit Fuel for 10-Year Life	767	349
Spacecraft Launch Weight	4,277	1,944
Transfer Orbit System (SPM)	22,780	10,355
Cradle	550	249
Total Weight In Shuttle	27,607	12,548

A rendering of the high power spacecraft configuration is shown in Figure 4.3-3. The length of the spacecraft is about 15 feet with solar cells folded.



ON-ORBIT WEIGHT	4277 lb
LENGTH	15 ft
MAXIMUM ARRAY POWER	11.1 kW
RF POWER	100 W/BEAM
ANTENNA	25 BEAMS, 1°
PERIGEE MOTOR	SPM-8
UNIT SPACECRAFT COST	$60M

Figure 4.3-3. Spacecraft for DTU System

4.3.3 Cost Analysis

The driving spacecraft cost parameters are shown in Table 4.3-4. When applied to the SAMSO cost model as shown in Table 4.3-5, it is determined that a spacecraft nonrecurring cost (including quality model) of $116 million is expected and that the recurring cost of each spacecraft is about $60 million. These values exceed that of the baseline configuration, which had development costs of $85 million and unit recurring costs of $36 million.

Table 4.3-4. DTU Spacecraft Cost Model Input Parameters (FDMA)

Spacecraft Subsystem Weights	
Communications	1,392 lb
Structure/Thermal	688 lb
TT & C	50 lb
Attitude Control/Propulsion	288 lb
Power (11,145 W BOL)	1,092 lb
Launch Requirements	
Spacecraft Launch Weight	27,607 lb
Spacecraft & Perigee Motor Length	21.5 ft

Table 4.3-5. Derivation of Spacecraft Costs (FDMA)

Subsystem	Basic Costs ($K)		Complexity Factors	Final Costs ($K)	
	Nonrecurring	Recurring		Nonrecurring	Recurring
Communication (1,393 lb)	23,043	11,902	2.03 NR 1.89 R	46,662	22,483
TT&C (50 lb)	1,395	745	1.22 NR 1.12 R	1,701	837
Power					
Basic 1,092 lb	15,255	2,400	1.00 NR 1.00 R	15,255	2,400
Array Cells	3,715	2,922	1.33 NR 5.64 R	4,952	16,771
AACS (288 lb)	11,860	3,829	1.15 NR 1.06 R	13,639	4,066
Structure (688 lb)	5,694	1,140	1.35 NR 1.38 R	7,664	1,571
	SAMSO Cost Model			89,873	48,128
				Mgmt 26,962	12,032
				116,834	60,160

The DTU FDMA space segment cost elements are summarized in Table 4.3-6. The associated earth terminal costs for 1000 terminals are obtained using the standard terminal cost breakdown shown in Table 4.3-7.

The combined system costs for a 10-year operating period are listed in Table 4.3-8. The total space segment costs of $473 million constitute 30% of the total program cost. The total earth segment cost for 1000 terminals, including operations and maintenance, is expected to be $1.081 billion, which is 70% of total program costs.

The cost spread by program year, including a three year development period, is shown in Table 4.3-9. A plot of the DTU FDMA cumulative costs is shown in Figure 4.3-4.

It is seen that 80% of the total costs are incurred before the end of the sixth program year (third year of on-orbit operations) whereas revenue is expected to start at a low level and increase over the operating period. This means that a major expense is incurred for the financing of the net investment.

Table 4.3-6. DTU Spacecraft Cost (FDMA)

Item	Cost ($)
Spacecraft	
Nonrecurring	116,834,000
Recurring Unit Cost	60,150,000
Prototype Refurbishment & Support	16,531,000
Perigee Motor	
SPM-8 Unit Cost	7,000,000
Launch Vehicle	
STS Pro Rata Unit Cost	17,533,000

Table 4.3-7. Standard Terminal Cost Element (FDMA)

Item	Cost ($)	
Antenna		
4.5m reflector, pedestal, feed & steptrack		20,200
Transmitters		
1 W power amplifier (16)	70,400	
10 W power amplifier	11,900	106,200
50 W power amplifier	23,900	
Receiver/Converters		
Low noise amplifier (2)	19,100	186,500
Up down converters (13)	167,400	
Digital Equipment		
Modulator/demodulator	42,800	67,800
Demand assignment processor	25,000	
Other		
Frequency standard, order-wire, control monitor, racks, cabling, power	36,700	287,100
Other site equipment	83,500	
Installation and checkout	125,200	
Initial spares	41,700	
		667,800

Table 4.3-8. DTU 10-Year System Costs

Item	Cost ($)	
Space Segment		
Spacecraft non-curring	116,834,000	
Prototype spacecraft refurbishment	16,531,000	
Flight model spacecraft (3)	180,479,000	
Perigee motors (3)	21,000,000	473,800,000
Pro rata STS launch (3)	52,599,000	
On-orbit incentives	62,747,000	
TT&C fixed & operations	23,610,000	
Terminal Segment (1000)		
Nonrecurring	3,970,000	
Fixed hardware	667,800,000	1,080,770,000
Operations & maintenance	409,000,000	
	1,554,570,000	

Table 4.3-9. Cost Spread for Direct-to-User System (FDMA)

Program Element	Program Year												
	1	2	3	4	5	6	7	8	9	10	11	12	13
Spacecraft													
a) Spacecraft nonrecurring	59.8	30.0											
b) Spacecraft flight models (3)		72.2	72.2	36.1									
c) Prototype refurbish				6.0	6.0								
d) 3rd launch support								3.0					
e) Storage				0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
f) STS launch pro rata (3)	7.0	14.0	14.0			3.5	7.0	7.0					
g) Perigee motor (3)		7.0	7.0				3.5	3.5					
TT&C													
a) Nonrecurring	2.3	1.1											
b) Fixed hardware		5.0	5.1										
Earth Terminals (1000)													
a) Nonrecurring	2.6	1.3											
b) Fixed hardware		35.0	61.7	111.8	258.7	200.3							
Operating Costs													
a) TT&C operation maintenance				1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
b) Terminals operation & maintenance				40.9	40.9	40.0	40.9	40.9	40.9	40.9	40.9	40.9	40.9
c) Spacecraft orbit incentives				6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3
Yearly Totals	71.8	165.6	160.0	202.3	313.1	252.2	58.9	61.9	48.4	48.4	48.4	48.4	48.4

Note: All figures in millions of dollars normalized to 1978 value.

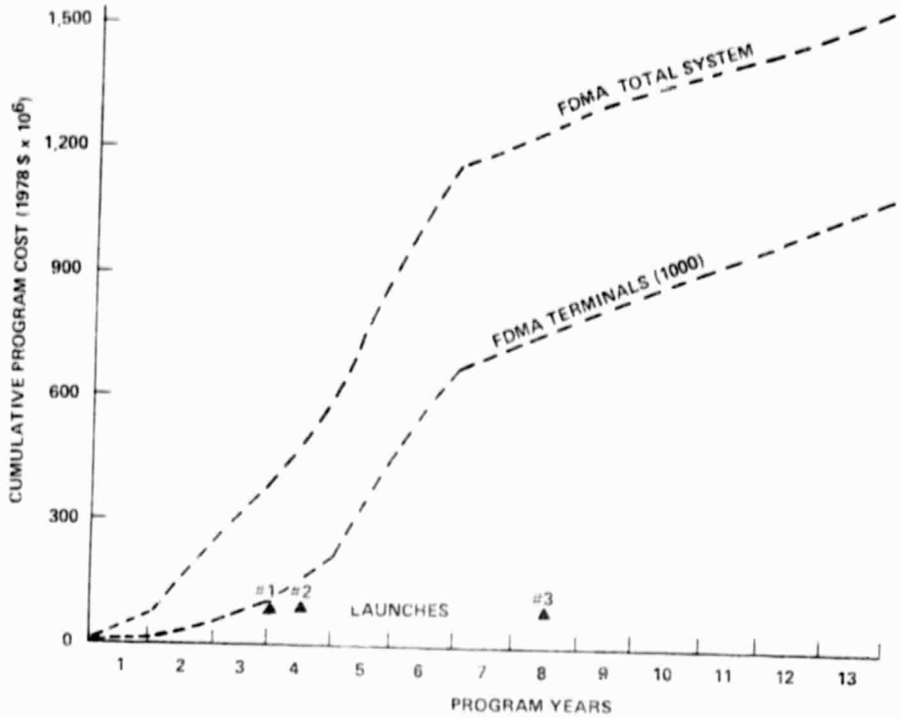
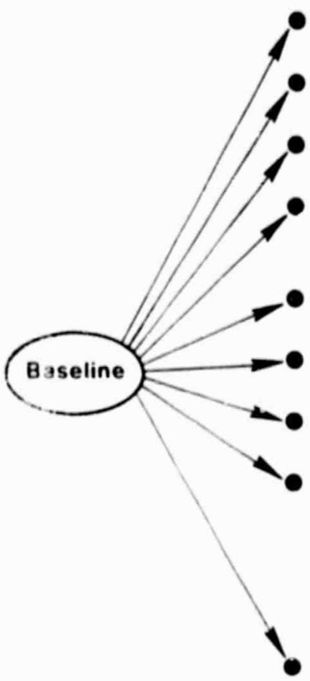


Figure 4.3-4. DTU FDMA Cumulative Costs

Subsection 4.4

Other Tradeoff Alternatives to Baseline DTU Configuration

A diagram of design alternatives for the baseline direct-to-user system configuration was shown in Figure 4.1-1. The baseline TDMA system and an alternate FDMA system were described in subsections 4.2 and 4.3. This subsection examines the performance and cost tradeoffs for other alternative candidate system configurations. A history of potential variances to the baseline is given in Figure 4.4-1.



Increase number of terminals	-	Service availability decreases
Increase spacecraft power	-	Small impact because of uplink limitations
Increase system capacity	-	Earth terminal diameter exceeds 5 meters - too large
Allocate extra channels to high-traffic beams	-	Should be incorporated for balanced system, increases switching matrix complexity
Skewed data capacity among beams	-	Feasible with variable switching dwell period
Increase number of beams	-	Switching matrix becomes excessive
Include onboard processing	-	Efficient - however, reliability compromised, 2nd generation
FDM modulation	-	Eliminates spacecraft switching – however, filters become excessive for large numbers of links
	-	Earth terminal transmitter power reduced, but frequency synthesizer added
Decrease communications link availability	-	Eliminate 5 dB down/15 dB up rain margin - reduces system cost

Figure 4.4-1. DTU Alternatives

The alternate configuration described in paragraph 4.4.1 increases the rf output power of the spacecraft to the maximum value consistent with the use of the IUS perigee motor. It is shown that an increase of +6 dB in spacecraft EIRP (100 W rf per beam) may be achieved. This can be used to increase performance or reduce costs of the earth terminals.

The alternate configuration of paragraph 4.4.2 increases the number of earth terminals and also the system throughput capacity. The economy of scale reduces the cost per circuit, but demand requirements may not be available for a first generation system.

The alternate configuration described in paragraph 4.4.3 would provide a variable link capacity per beam. One method would increase the dwell time for interconnect of antenna beams between regions of high data capacity. For example, the interconnect of Chicago-New York City and Los Angeles-New York City beams could be several times that of the average dwell period. Another technique would provide a skewed data communications rate per beam which matches the market demand per beam. Another technique would partially match the skewed distribution of users among antenna coverage beams by assigning an additional five transponder channels to the high user density areas.

The alternate configuration of paragraph 4.4.4 provides low cost communications only during clear weather conditions.

Other alternative configurations of merit, but not discussed here, would include the following:

a. Use of rf repeater satellite rather than demodulating to baseband
b. Expanding the number of antenna beams to 40 or more
c. Use of nonuniform antenna beams
d. Reduction of communications performance to 99% availability
e. Use of buffer data storage in the spacecraft for more efficient bandwidth allocation

4.4.1 Alternate Configuration: Increased Spacecraft Power

In this alternate configuration the spacecraft power has been increased to the maximum value (100 W per beam), which is consistent with launch from the Shuttle Orbiter with either the IUS perigee motor or the SPM-B. The maximum capability of either would place 5000 lb of spacecraft weight into synchronous orbit.

The spacecraft and launch weight budget is detailed in Table 4.4-1. The total weight in the Orbiter is expected to be 39,200 lb, which is 60% of the Orbiter maximum weight capability. This increases the pro rate shuttle costs by about $5.5 million per launch relative to the baseline design.

The spacecraft power budget of Table 4.4-2 shows an allocation of 100 W rf per beam for each of 25 beams. The required solar array output at the beginning of a 10-year life is 14.4 kW. This requires an array area of 96 m^2, which could be implemented with two array wings of approximately 10 ft x 53 ft dimensions each.

Table 4.4-1. Spacecraft and Launch Weight Budget

Item	Weight (lb)	Weight (kg)
Spacecraft Subsystems		
Communications	1,505	683
TT&C	50	23
Electrical power/ electrical integration	1,195	542
Structure/thermal/ mech integration	1,140	517
Attitude control/RCS	315	143
Spacecraft dry weight	4,205	1,907
Fuel for 10 yr life	1,035	469
Spacecraft on-orbit weight	5,240	2,376
Transfer orbit systems (SPM-8)	33,400	15,150
Cradle	550	249
Total weight in shuttle	39,190	17,775

The larger spacecraft dictates increased space segment costs. The results of applying the SAMSO cost model to this configuration reveal that the unit spacecraft recurring cost increases to $43 million each.

However, the increased satellite EIRP does not decrease the unit earth terminal costs significantly because the limiting segment of the communications relay is the uplink from the terminal to the satellite during heavy rain periods. This differs from conventional satellite links at lower frequency bands, which are not affected by rain attenuation and which are generally downlink constrained. A less costly low noise amplifier may be used at a per unit cost of about $3000 (compared with $16,000 for the baseline 230 K noise figure receiver). With a redundant unit in each of 1000 terminals, this would result in an overall ground segment savings of $26 million.

The net system cost impact of increasing the spacecraft power per beam for DTU operation with TDMA is shown in Table 4.4-3. The communications link capacity of 150 Mb/s remains fixed for this tradeoff. It is shown that if the spacecraft power is increased by +3 dB per beam (to 50 W rf), then the extra cost of the bigger spacecraft segemnt exceeds that of a savings in lower cost receiver amplifiers in 1000 terminals by $43 million. If the spacecraft power is increased by +6 dB (to 100 W rf per beam), then an extra systems cost of $53 million is incurred.

If the extra spacecraft performance is offset by using a smaller earth terminal diameter which matches the downlink performance savings, the earth station transmitter power must be increased. This results in a large net increase in unit terminal costs and the overall system costs are increased by $217 million.

It is concluded that an increase of spacecraft power does not reduce overall system costs for a 1000 terminal network. The earth terminals are uplink limited and hence additional power from a larger spacecraft on a downlink is of small benefit.

Table 4.4-2. Spacecraft Power Budget

Item	Power (W)
Power Amplifiers (25 of 100 W RF)	8,400
Other Communications Subsystems	500
Other Spacecraft Subsystems	680
Battery Charging	500
Total Spacecraft Load	10,080
Array Design Margin (5%)	500
Allowance For Degradation of Cells (10 yr)	3,910
Total Array Output (BOL) ($95 m^2$ array)	14,490

Table 4.4-3. Increased Spacecraft Power Tradeoff (DTU TDMA)

Modification: Increase of S/C RF power saves on user terminal costs
Communications link capacity fixed

System cost impact:	S/C RF Power + 3 dB	S/C RF Power + 6 dB
a. Low-cost terminal LNA	+ $ 43 M	+ $53 M
b. Decrease terminal dia. and increase transmitter power	+ $217 M	
c. Decrease terminal dia. and increase S/C G/T	+ $ 57 M	

Conclusions:

- Increase of S/C power does not reduce total system cost for 1000 terminals
- Small savings in user terminals because uplink power limited

4.4.2 Alternate Configuration: Increased System Size and Capacity

A unit spacecraft is capable of handling more than the baseline throughput data rate of 3.5 Gb/s. Thus, as more terminals are added, the resource availability of the spacecraft per terminal can remain fixed by increasing the data rate.

An economy of scale is achieved with larger systems as shown in Table 4.4-4 because a moderately larger spacecraft segment cost is shared by a greatly increased number of user terminals. For example, the space segment cost of the baseline configuration is $333 million. A doubling of spacecraft capacity to 7.0 Gb/s increases the spacecraft segment cost to $459 million. This represents a 38% cost increase; however the number of equivalent terminals may be increased 100%.

In a similar manner a fourfold increase in data capacity (achieved by frequency diversity within a beam) leads to total system costs that increase from $1.236 billion to $3.392 billion, ie, an increase by a factor of only 2.7.

In conclusion, the economy of scale reduces the equivalent cost per circuit, but large user demand is yet to be established.

Table 4.4-4. System Data Capacity Tradeoff (DTU TDMA)

Modification: Impact of change in number of terminals
Fixed capacity per SATCOM link

Cost Impact:	Number of User Terminals 1,000	2,000	4,000
System capacity	3.5 Gb/s	7.0 Gb/s	14 Gb/s
Space segment cost	$ 332 M	$ 459 M	$ 569 M
Terminal costs	$ 894 M	$1,600 M	$2,823 M
Total costs	$1,226 M	$2.059 M	$3,392 M

Conclusions:

- Economy of scale reduces cost per circuit but user demand must be established
- Baseline capacity may be increased x4 thru frequency reuse

4.4.3 Alternate Configuration: Variable Capacity per Beam

The baseline DTU configuration assumes equal distribution of traffic per beam; ie, each 1° half power beamwidth accommodates 140 Mb/s communications data rate. A user services demand model by beam area has not yet been defined. Several techniques may be used to match the spacecraft capability to a nonuniform distribution of users.

The first method would be to use a nonstandard dwell time for interconnect of antenna beams between regions of high data capacity. For example, the interconnect of beams containing Chicago and New York City could be several times longer than that of the average dwell period. It should be noted that the long interconnect periods would require that other interconnect periods be shorter than normal. The interconnect of the Utah area beam with the New York City beam would be a candidate for short period assignment.

A second method would allocate one or more additional 140 Mb/s data channels for high capacity beam areas — using frequency diversity for separation. For example, a 25-beam system could be implemented with 30 channels of 140 Mb/s data. The New York area beam could have three channels, Los Angeles and Chicago areas two channels, and all other beams a single channel capacity.

A third method would be to have a symmetrical pattern of coverage beams from the spacecraft but to have a wide range of link capacity per beam. The TDMA burst rate may then range from 50 Mb/s in regions of low capacity requirements up to 500 Mb/s for regions of high capacity. This would lead to a variance in the performance and cost of earth terminals located within the various beams. The complexity of spacecraft interconnect switching is also increased.

4.4.4 Alternate Configuration: Reduced Communications Availability

It rains less than 1.5% of the time at an average site within CONUS. One alternative for minimizing 18/30 GHz system costs would be to eliminate rain margins entirely and only communicate during clear weather. (Important real-time information would be sent via alternate C-band satcom links or via terrestrial network facilities.) This would reduce the unit costs of the earth terminals to $415,000 as shown in Table 4.4-5.

The costs are in 1978 dollars for a 150 Mb/s TDMA system burst rate with production in lots of 100. No uplink rain margin (15 dB) is included and hence the antenna dish size may be reduced to 3 m, and the maximum transmitter power level is reduced to 100 W. Spacecraft power per beam is 25 W.

This clear weather operation configuration would reduce terminal costs by $103,000 each compared with the baseline terminal. This is a total savings for a 1000-terminal network of $103 million. The tradeoff savings of 20% in unit terminal costs must be weighed against the reduced communications availability. Current assessment of this tradeoff would indicate that the customer would prefer the increased availability (to 99.5%) of the baseline design in return for the greater price.

Table 4.4-5. Standard Terminal Cost Elements (Clear Weather Operation Only)

Item	Cost ($)	
Antenna		
3 meter reflector, pedestal, feed, & steptrack		15,000
Transmitters		
100 watt power amplifier (2)	32,000 ea	64,000
Receiver/Converters		
Low noise amplifier (2)	8,000 ea	39,000
Up-down converters	23,000	
Digital Equipment		
Mod/demod	40,000	92,000
Digital Subsystem	12,000	
Demand assignment processor	40,000	
Other		
Frequency standard, orderwire, control monitor, racks, power	37,000	205,000
Other site equipment	60,000	
Initial spares	28,000	
Installation and checkout	80,000	
		415,000

SECTION 5

CRITICAL TECHNOLOGY AND REQUIRED DEVELOPMENTS

This section provides an assessment of those technologies that are critical to the implementation of the system concepts described for trunking application in Section 3 and for direct-to-user (DTU) application in Section 4. The development recommendations are divided into four categories:

- Key Technology for 1st Generation System
- Key Technology for Advanced Follow-On Systems
- Operational Concepts Analysis
- Experimental Flight Test Program

Each is described in turn.

5.1 KEY TECHNOLOGY FOR FIRST GENERATION SYSTEM

The key technology developments identified for support of baseline FDMA trunking systems at 18/30 GHz are listed in Table 5-1. The critical items include a multiple beam spacecraft antenna with half power beamwidth of 0.3° or less. Good isolation between beams is required; hence low sidelobe techniques coupled with polarization diversity may be employed. The spacecraft power amplifier is required to have long term reliability and to provide about 1 to 5 W rf output from solid state devices. Low-loss multiplexer combiner techniques will be required. The spacecraft digital data handling system must accommodate baseband digital data rates of up to 274 Mb/s with QPSK modulation. A space diversity earth terminal is required; hence techniques for maintaining bit integrity during switchover between terminals should be developed. The control of earth terminal transmitter power output level during rain conditions should also be examined.

The key technology developments identified for support of baseline TDMA DTU systems at 18/30 GHz are listed in Table 5-2. The critical items include a multiple beam satellite antenna for full CONUS coverage, a new satellite power amplifier with 25 to 100 W output at 18 GHz, demodulation/remodulation equipment suitable for satellite use, and a K_A-band nd user terminal that can be produced in quantity at low cost.

5.2 KEY TECHNOLOGY FOR ADVANCED FOLLOW-ON SYSTEMS

The following additional technology developments have been identified to improve system capacity and reduce costs for second generation systems:

a. Variable satellite transmitter power

b. Onboard signal processing

1. Multiple carrier demodulation
2. Store and forward
3. Cross connect of DTU and trunking circuits

c. Dual frequency band antennas with smaller spot beam

d. High peak power/low duty cycle amplifiers for low-cost earth terminals

Table 5-1. Trunking Technology for First Generation System

S/C Antenna:	- Multiple spot beams of 0.3° beamwidth - Low sidelobe/polarization diversity for isolation
S/C Power Amplifier:	- Solid state with 1 to 5 watt RF output at 18 GHz - Low-loss RF multiplexer
S/C Data Handling:	- Channel equalization at 274 Mb/s - 25 Gb/s thruput capacity
Earth Terminal:	- Diversity switching techniques for bit integrity - High-speed modems

Table 5-2. DTU Technology for First Generation System

S/C Antenna:	- Overlapping multiple beams for full CONUS coverage - Feed layout, beam control, polarization diversity
S/C Power Amplifier:	- 25 to 100 watts RF per beam at 18 GHz - Multichannel
S/C Data Handling:	- High reliability/redundancy - Demodulation/remodulation - Baseband switching matrix
User Terminals:	- Low-cost power amplifiers at 30 GHz, variable power control - Low-cost autotracking and timing - Low-cost manufacturing/checkout techniques - Unattended operation

A technique for efficiently varying the satellite transmitter power would allow matching the individual satellite channel capacities to the instantaneous traffic load and required rain attenuation margin, thereby increasing total satellite throughput.

The use of advanced signal processing techniques on the satellite would allow optimizing the uplinks and downlinks separately. Work performed under a separate study of store-and-forward system techniques indicates potential gains in store-and-forward processing for burst (packet) type traffic.

Any dual frequency band concept would require development of low-cost dual-frequency feeds for the ground terminal antenna and possibly for the satellite also. The Japanese CS satellite used a dual frequency C-band and K_A-band satellite antenna.

Finally, for the direct-to-user terminal operating in a TDMA mode, the need exists for a low-cost high-power amplifier capable of delivering high peak powers with low duty cycle bursts of carrier at 30 GHz.

5.3 OPERATIONAL CONCEPTS ANALYSIS

This study investigated two system configurations: trunking and direct-to-user. A more cost-effective approach might be to combine the payloads for the two services on one satellite. The transponders would be cross-connected, enabling access into the trunking system by a single user.

Figure 5-1 shows some of the alternative concepts that should be investigated in a future study. Included are satellite multiple beam antennas with a scanning beam added (the BTL concept) and different types of multiplexing.

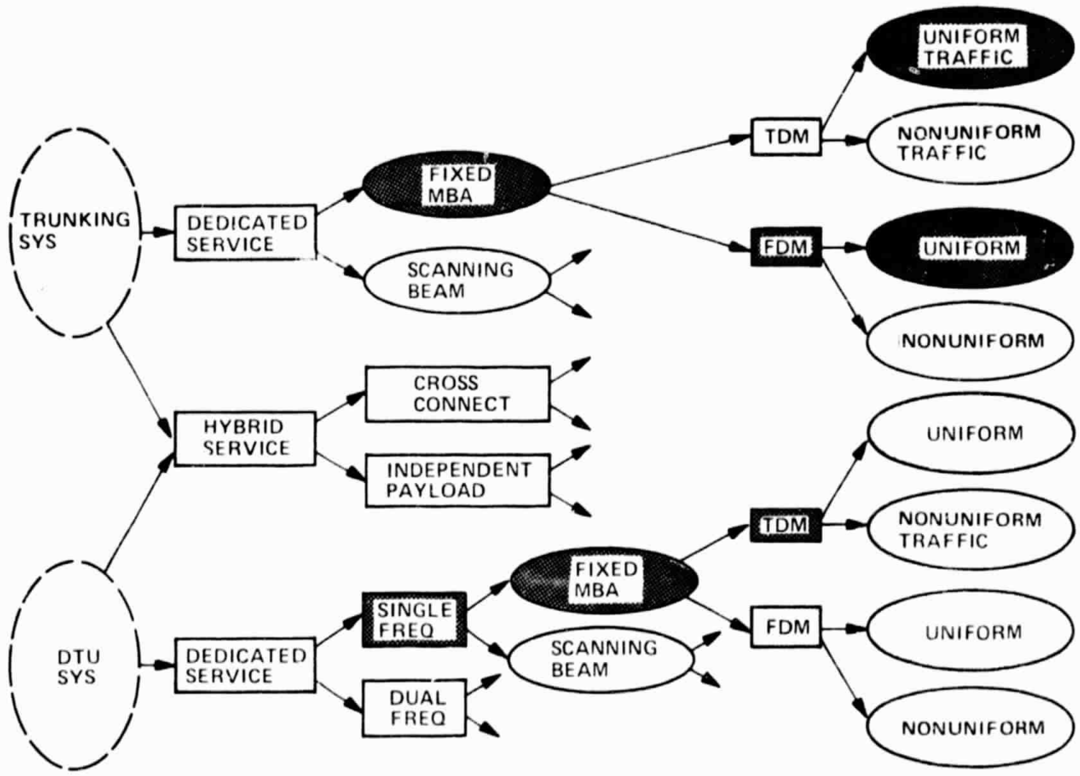


Figure 5-1. Operational Concepts Analysis

Investigation of a dual frequency band concept (C plus K_A) is also recommended, where C-band carries high priority traffic during heavy rainfall periods.

In the current study, a uniform traffic model (both geographic and time) was used as a basis for system evaluation and comparison. Future studies should make use of more realistic nonuniform traffic models, incorporating the results of recent work performed for NASA by Western Union and ITT.

5.4 EXPERIMENTAL FLIGHT TEST PROGRAM

To reduce the risk of new technology on an operational 18/30 GHz satcom system, it is recommended that key items be evaluated through an experimental flight test program. Specific technology items would be identified after completion of a user demand/concept analysis phase. In order to obtain full benefits of a test program, it is important to initiate detailed planning of tests as early as possible.